ERDC/CHL TR-15-2

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Monitoring Completed Navigation Projects (MCNP) Program

Hydraulic Evaluation of Marmet Lock Filling and Emptying System, Kanawha River, West Virginia

Richard L. Stockstill

April 2015

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Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Abstract

A hydraulic analysis of the Marmet Lock filling and emptying system was performed. Evaluation of the culvert system was considered important because the lock design is a new In-chamber Longitudinal Culvert System (ILCS) that is found only on one other project, the Ohio River's new McAlpine Lock. The purpose of this study was to evaluate the hydraulic conditions within the lock filling and emptying system during locking operations. A numerical model of the lock culvert system was developed to provide velocity and pressure information throughout the system. The model was validated with field data collected earlier in the study. Hydraulic information for both filling and emptying operations with various valve operations was computed. The numerical model results indicate that the hydraulic conditions are not significantly different from those anticipated during the project's design phase.

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Preface

The investigation reported herein was conducted as part of the Monitoring Completed Navigation Projects (MCNP) program under MCNP work unit *Marmet Locks and Dam, Kanawha River, West Virginia*. Overall program management of the MCNP was provided by Headquarters, U.S. Army Corps of Engineers (HQUSACE). The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), was responsible for technical and data management, and support for HQUSACE review and technology transfer. The HQUSACE program monitor for the MCNP program at the time of this study was James E. Walker, Chief, Navigation Branch, HQ. W. Jeff Lillycrop, CHL, was the ERDC Technical Director for Navigation. MCNP program manager during the conduct of this study was Dr. Lyndell Z. Hales, Technical Programs Office, CHL.

This research was conducted under the general direction of José E. Sánchez, Director, CHL; Dr. Kevin M. Barry, Deputy Director, CHL; Dr. Jackie S. Pettway, Chief, Navigation Division, CHL; and Howard E. Park, acting Chief, Navigation Branch, CHL.

The principal investigator for the *Marmet Locks and Dam, Kanawha River, West Virginia* work unit was Donald C. Wilson, Harbors, Entrances, and Structures Branch, CHL. The field data collection effort was led by Terry N. Waller, Field Data Collection and Analysis Branch, CHL. This investigation and subsequent report was completed by Dr. Richard L. Stockstill, Navigation Branch, CHL. A set of field data was collected in August 2010 and a second set was collected in August 2011. The numerical model study was conducted between July and September, 2013. This report was prepared by Dr. Stockstill.

LTC John T. Tucker III was Commander of ERDC. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
miles (US statute)	1.609344	kilometers

1 Introduction

1.1 Monitoring Completed Navigation Projects (MCNP) Program

The goal of the Monitoring Completed Navigation Projects (MCNP) program (formerly the Monitoring Completed Coastal Projects (MCCP) program) is the advancement of coastal and hydraulic engineering technology with respect to U.S. Army Corps of Engineers (USACE) requirements. The program is designed to determine how well projects are accomplishing their purposes and resisting attacks by their physical environment. These determinations, combined with concepts and understanding already available, will lead to the creation of more accurate and economical engineering solutions to coastal and hydraulic problems, thus strengthening and improving design criteria and methodology, improving construction practices and cost-effectiveness, and improving operation and maintenance (O&M) techniques. Additionally, the monitoring program will identify where current technology is inadequate or where additional research is required.

To develop direction for the program, USACE established an ad hoc committee of engineers and scientists. The committee formulated the objectives of the program, developed its operation philosophy and recommended funding levels, and established criteria and procedures for project selection. A significant result of this committee was a prioritized listing of problem areas to be addressed, which is essentially a listing of the areas of interest for this program.

USACE offices are invited to nominate projects for inclusion in the monitoring program as funds become available. The MCNP program is governed by Engineer Regulation 1110-2-8151 (Headquarters, USACE (HQUSACE) 1997). A selection committee reviews and prioritizes the nominated projects based on criteria established in the regulation. The prioritized list is reviewed by the program monitors at HQUSACE. Final selection is based on this prioritized list, national priorities, and the availability of funding.

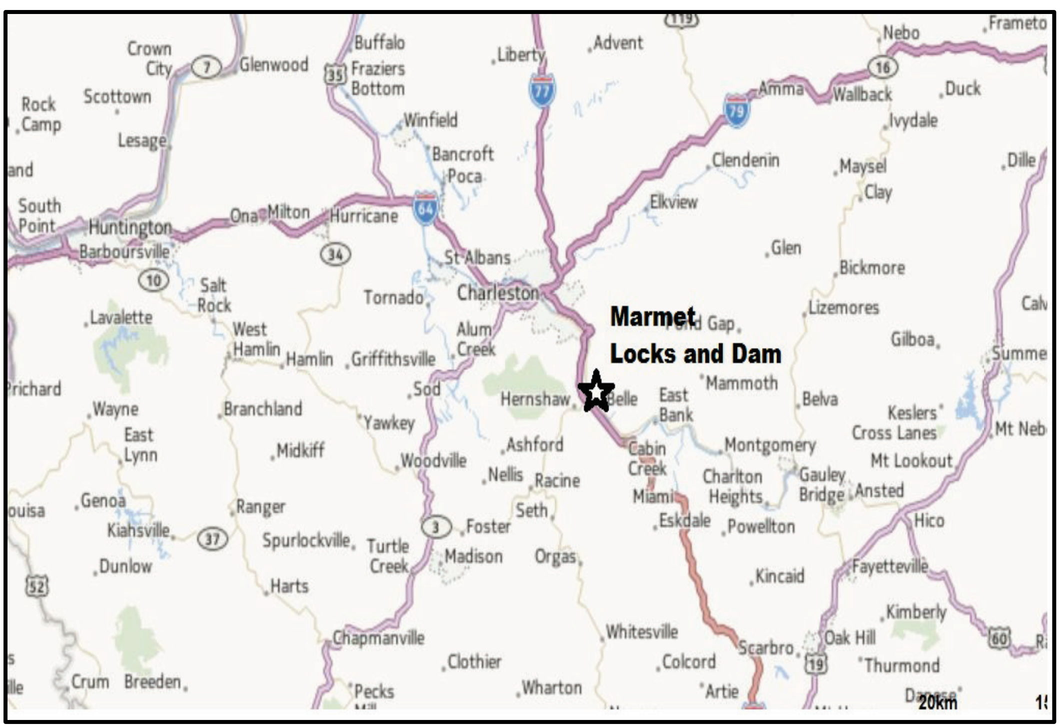
The overall monitoring program is under the management of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), with guidance from HQUSACE. An individual monitoring

project is a cooperative effort between the submitting District and/or Division office and CHL. Development of monitoring plans, and conduct of data collection and analyses are dependent upon the combined resources of CHL and the District and/or Division.

1.2 Project Description

The Marmet Locks and Dam project is located on the Kanawha River, about 68 miles above the mouth of the river (Figure 1). The project is about 9 miles upstream of Charleston, West Virginia, and approximately 27 miles from the head of navigation. The upper pool extends upstream 15 miles to the London Locks and Dam, and the lower pool is formed by the Winfield Locks and Dam about 36 river miles downstream. The original twin locks built in 1934 measured 56 feet (ft) wide by 360 ft long. During the 1930s, this was large enough to handle the traffic of the Kanawha River. Over the years, barges have increased from the 175 ft long standard barge to the 35 ft wide by 195 ft long jumbo barge. These new barges can carry up to 2,000 tons (one and a half times the capacity of the standard barge of the 1930s). This larger barge, combined with the increase in traffic, created a bottleneck effect at the Marmet Locks and Dam.

Figure 1. Marmet Locks and Dam, Kanawha River, West Virginia, vicinity map.



The project consists of the new 110 ft by 800 ft lock, the two original 56 ft by 360 ft locks, a non-navigable gated dam, and a three-unit hydroelectric power plant (Figure 2). The dam is 557 ft long and consists of five roller-type gates, each of which spans 100 ft between concrete piers. The power plant is owned by Kanawha Valley Power Company and is capable of producing 144,000 kilowatts. The new lock is located on the east (right descending) side of the old lock and has a design lift of 24.0 ft. The design-lift condition occurs with a normal upper pool elevation of 590 ft[1] and a normal lower pool elevation of 566 ft.

Figure 2. Marmet Locks and Dam, Kanawha River, West Virginia.

The lock features a through-the-sill intake, an in-chamber longitudinal culvert filling and emptying system, and a discharge manifold located in the lower lock wall. The new lock construction also included replacing the upper and lower guide walls.

The USACE was authorized by Congress (Water Resource Development Act of 1996) to build a larger lock adjacent to the existing lock to accommodate increased traffic at Marmet Locks and Dam. The contract for the Lock was awarded on 28 May 2002, and construction began in the summer of 2002. The new lock became operational on 22 January 2008. It is estimated that

[1] All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

the average transit time has been reduced from about 4 hours (hr) to about 0.8 hr. In 2010, more than 16.4 million tons of commerce locked through Marmet.

Many design features were incorporated into the new Marmet Lock project as construction costs savings. Placing the lock intake in the upper miter gate sill saved a large volume of concrete that would have been required if the intakes were placed in the traditional position within the upper approach walls. Also, placing the filling and emptying culverts inside the lock chamber allowed the flexibility of using innovative construction techniques for the lock walls. The more conventional lock wall construction calls for large concrete gravity walls with the culverts inside the walls.

Details of the lock filling and emptying system are shown in Figure 3. The system begins with a multi-ported intake located in the upstream face of the miter gate sill. Each port is 8.17 ft wide by 15 ft high at the face of the intake. Each half of the intake transitions to 13 ft wide by 15 ft high culverts located outside the lock walls where the filling valves and bulkheads are located. Flow to the culverts is controlled by vertical-lift (Stoney) valves. Downstream from the filling valve, the culverts curve back into the lock chamber and continue to the filling and emptying manifolds.

Each of the two filling and emptying manifolds are 13 ft wide by 15 ft high culverts with 11 pairs of ports located in both the upstream and downstream portions of the lock chamber. The upstream ports contain additional port extensions to direct the filling jets normal to the culverts. Figure 4 shows a photograph of the in-chamber longitudinal culverts. Downstream from the filling and emptying manifold, the culverts turn back outside the lock walls to accommodate the emptying valves and bulkheads (Figure 3). Each culvert ends at the discharge outlet which is a multiported diffuser manifold whose face is located along the lock wall in the lower approach (Figure 3).

1.3 Vertical-Lift Valves

The filling and emptying system for the new Marmet Lock uses vertical-lift valves for flow control. A general sketch of a vertical-lift culvert valve is shown in Figure 5. The dimensions of the Marmet Lock are such that the valve width, W, is 13 ft and the height, B, is 15 ft. The valve position is often given as b/B, the ratio of opening-to-culvert height. The primary advantages of the vertical-lift valve are that maintenance can be performed without

Figure 3. Marmet Lock filling and emptying system.

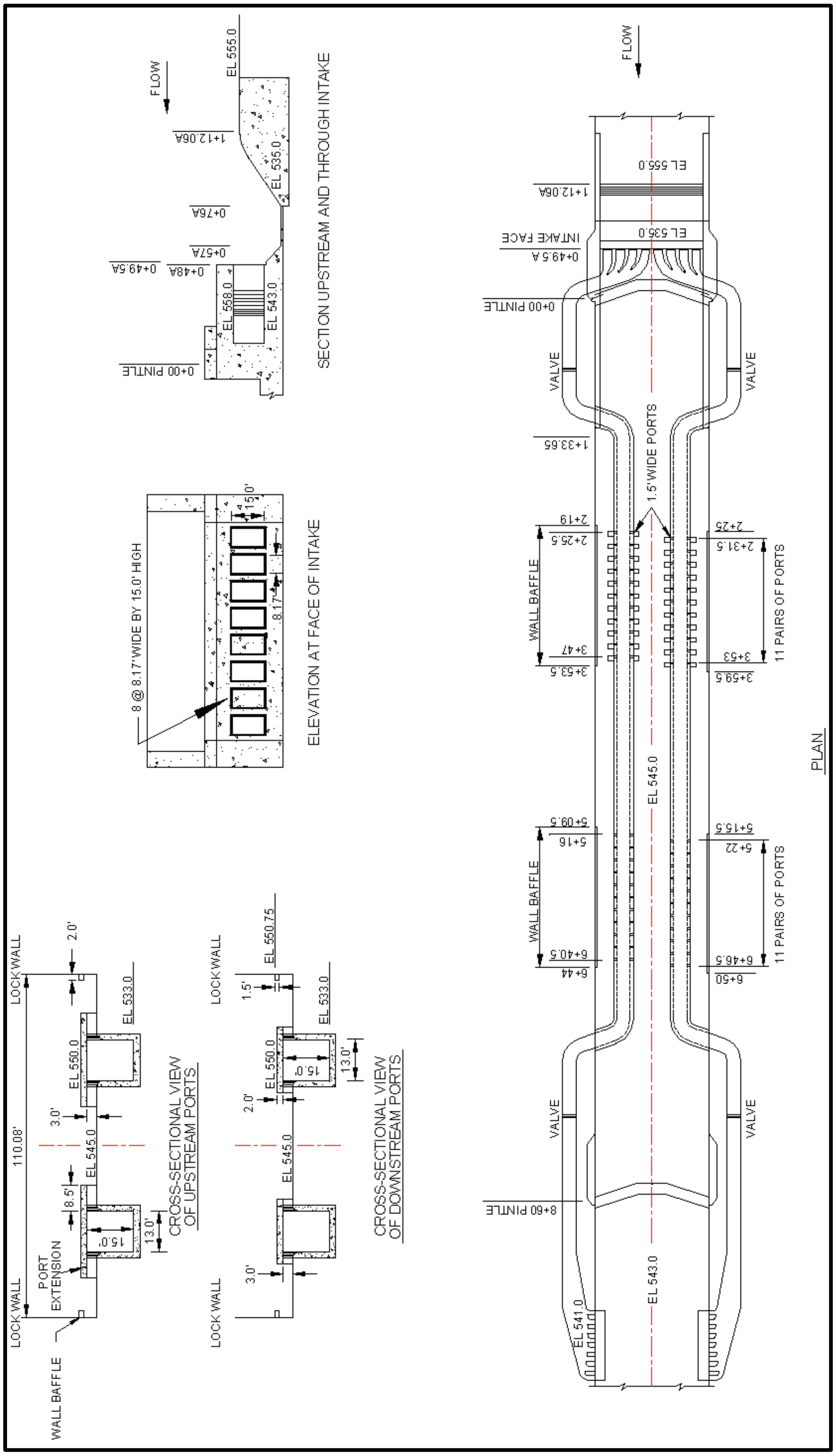
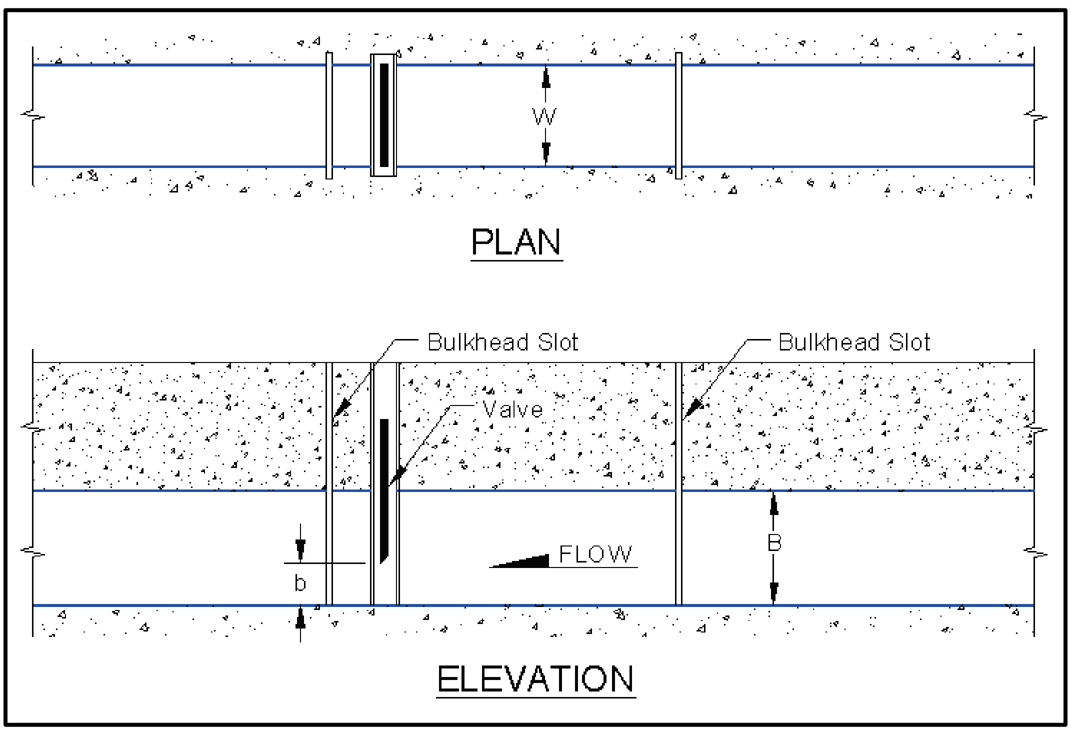


Figure 4. Dry bed view of the Marmet Lock in-chamber longitudinal culvert system, looking downstream.

Figure 5. Vertical-lift lock culvert valve.



taking the culvert out of service, and a large recess such as a valve well is not required as with tainter valves (Headquarters, U.S. Army Corps of Engineers 1975). Having a spare vertical-lift valve at the lock is also much less expensive than for other valve types. Post-1960 lock design has rarely included vertical-lift valves, so there is little experience with the relative high frequency of operations. Virtually all modern locks operated by the USACE use reverse tainter valves to control the lock filling and emptying system flows (Davis 1989). However, the innovative culvert design of the Marmet Lock called for vertical-lift culvert valves. The primary reason for using vertical-lift valves was the lack of space to incorporate a reverse tainter valve in the monolith portions of the culverts.

1.4 Purpose and Scope

The purpose of the current study is to provide an understanding of the lock filling and emptying system's performance, and to provide hydraulic information to design engineers of lock systems. Previously-published laboratory and field data, along with computational flow model results, have been gathered to provide a source of design and evaluation information.

The Marmet project has several unique and innovative features. Details of the filling and emptying system are provided on the plan and profile drawing of Figure 3. The filling system is a one-of-a-kind, through-the-sill system with vertical-lift (stoney) valves and longitudinal in-chamber culverts. The upper guide wall is constructed of long-span, post-tensioned concrete beams. Because of the unique nature of these components, monitoring was necessary to determine if the lock is functioning as designed, and if improvements could be made to this type of construction in the event it is used on future projects. Knowledge gained from this study will improve the design and evaluation of future navigation locks employing innovative design concepts.

1.5 Approach

The filling and emptying system of Marmet Lock was evaluated using the one-dimensional (1-D) unsteady flow LOCK SIMulation model (LOCKSIM) (Schohl 1999). The approach taken was to construct a numerical model of the Marmet Lock system, validate the model with field data, and then investigate hydraulic conditions with various operational schemes for both filling and emptying. Information gathered from previously published

physical and numerical studies of the Marmet Lock supplemented field data to develop an understanding of the new lock's performance.

This numerical model evaluation of Marmet Lock's performance under various operating schemes constituted only one task of the overall investigation of the new Marmet Lock filling and emptying system. Other aspects of the MCNP study are reported by Wilson et al. (in preparation).

2 Previous Investigations

2.1 Physical Model

The design process of the Marmet Lock included evaluation of the hydraulic aspects with a 1:25-scale physical model. The physical model study (Hite 1999), conducted at CHL, reproduced 600 ft of the upstream approach, including a portion of the right guide wall and the left guard wall. The intakes, miter gates, entire filling and emptying system, including culverts and valves, discharge outlet manifold, and approximately 300 ft of the topography downstream from the outlet were also reproduced. Photographs of the lock chamber and the right culvert filling valve are provided in Figures 6 and 7, respectively.

The physical model study evaluated innovative features that included a through-the-sill intake, an in-chamber longitudinal filling and emptying system, and a conventional sidewall discharge manifold. The purpose of the model study was to evaluate and make modifications to the filling and emptying system, if necessary, to provide a design that was acceptable to the USACE and the towing industry.

The model study was specifically conducted to evaluate vortex tendencies at the through-the-sill intake, determine filling and emptying times for various valve speeds, measure pressures in the culverts, and to document lock chamber performance. Chamber performance was based primarily on hawser forces exerted on a moored tow, movement of unmoored (free) tows in the lock chamber, and roughness of the water surface. Evaluation of the various elements of the lock system was based on data obtained during typical filling and emptying operations. Energy-loss coefficients were quantified using fixed-head (steady-flow) conditions with the culvert valves and/or miter gates fully opened or fully closed.

Pressure cells were used to measure instantaneous pressures in the culvert just downstream of a filling valve, and to record water-surface elevation in the lock chamber. Culvert pressures downstream of the valve were measured during both filling and emptying operations. No undesirably-low pressures were recorded. The pressure cells located at the upstream end, center, and downstream end of the lock chamber measured the water-surface variations with time. Pressures were also measured using

piezometers placed at particular locations in the system. The experimental results demonstrated that the design provided a balanced head throughout the system for the various filling and emptying operations tested.

Figure 6. The 1:25-scale model of Marmet Lock filling and emptying system (Hite 1999).

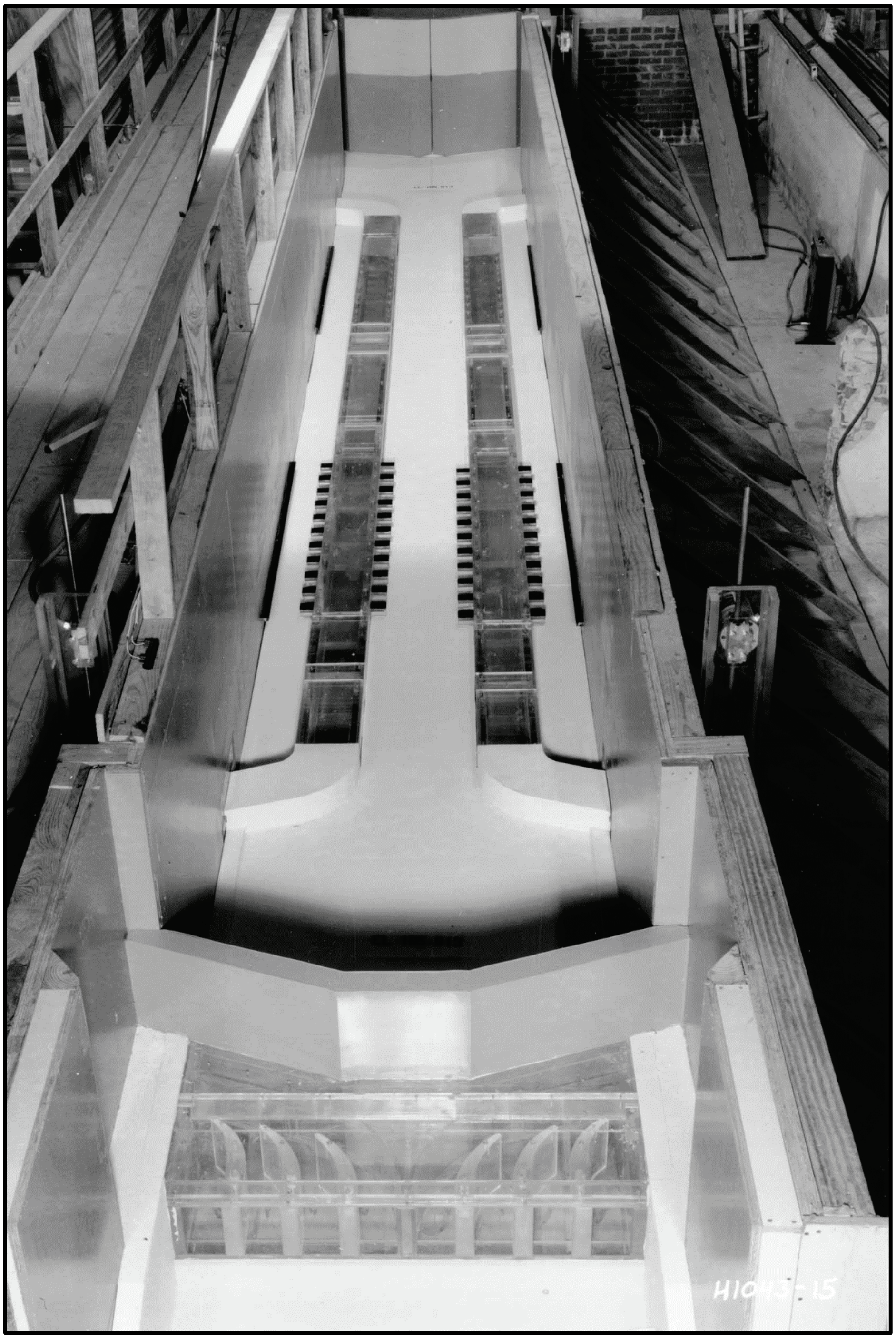
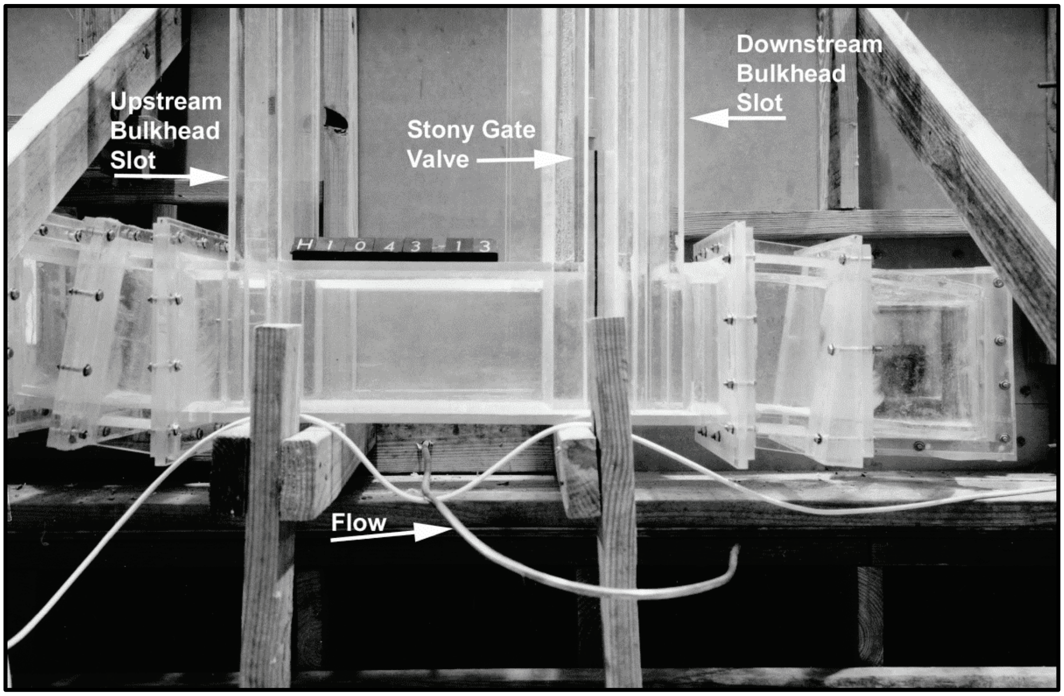


Figure 7. The 1:25-scale model of Marmet Lock, side view of culvert between intake and filling valve (Hite 1999).



The physical model reproduced an early lock design wherein the entire project was expressed in the SI System of Units, which was commonly referred to as “hard metric.” This hard-metric design used meters rather than feet as the primary units of length such that the culverts were specified as being 4-meters (m)- (13.12 ft) wide by 4.5 m (14.76 ft) high. During project development, the primary system of units was changed to the U.S. Customary System of units. The final design called for 13 ft wide by 15 ft high culverts. Therefore, components of the physical model study and the prototype are slightly different in size and shape.

Additionally, model and prototype valve operation speeds are different. The physical model studied hydraulic conditions with 2-, 4-, and 8-minute (min) valve operations, whereas the prototype normally operates with a 3 min valve speed and uses a 4 min valve during single-valve operations. The model and prototype differences in geometry and valve operations render it difficult to make meaningful comparisons between the two. However, the physical model study reported particular non-dimensional hydraulic coefficients that were used as part of the numerical model study. The pressure measurements obtained throughout the filling and emptying system during steady-flow conditions were used to determine the head losses for the system components.

2.2 Computational Flow Models

After completion of the physical model study, the laboratory data were used to evaluate computational flow models as part of separate research efforts supported by HQUSACE. Besides the comprehensive 1:25-scale physical model study, components of the new Marmet Lock filling and emptying system were studied using three-dimensional (3-D) computational flow models. These 3-D flow models used the conservation of mass and momentum, in the form of the Reynolds Averaged Navier-Stokes (RANS) equations, to calculate the pressure and velocity components throughout the flow domain. The Marmet Lock's complex geometry and flows provided challenging test cases for evaluation of computational flow solvers. The physical model study provided data for validation. Research studies have included a 3-D model of steady flow through the intakes, and one of the unsteady flows generated when a lock culvert valve is opened.

2.2.1 Intake Model

A 3-D computational flow model of the Marmet Lock intake structure was reported by Stockstill and Berger (2000). The model included 215 m of the upper approach, the upper miter gates and recesses, the intake ports, and filling system culverts (Figure 8). The 3-D RANS equations were discretized on tetrahedral cells that described the flow domain. The complicated geometry required the use of computational mesh cells that varied in size over several orders of magnitude.

The flow in the approach channel is slow and deep. As flow approached the intake, it crossed over an emergency bulkhead sill before entering the six intake ports located on the face of the miter gate sill. The intake split the flow into two culverts, each having three intake ports. The 4.0 m wide by 4.5 m high culverts simultaneously circled around the miter gate pintles and dropped down to the lock floor elevation through complicated horizontal and vertical curves. The flow accelerated as it entered the intake ports. Further accelerations occurred as the port flows merged into a single culvert on each half of the structure. These accelerations are shown in the velocity contours along a plane located in the center of the culvert (Figure 9). Pressure variations are illustrated on the contours in Figure 10. The computational model results were compared to laboratory data from Hite (1999). Flow distributions and pressure drops were determined. The computational flow model accurately reproduced the pressure distribution within the structure.

Figure 8. CAD model of Marmet Lock approach and intake (Stockstill and Berger 2000).

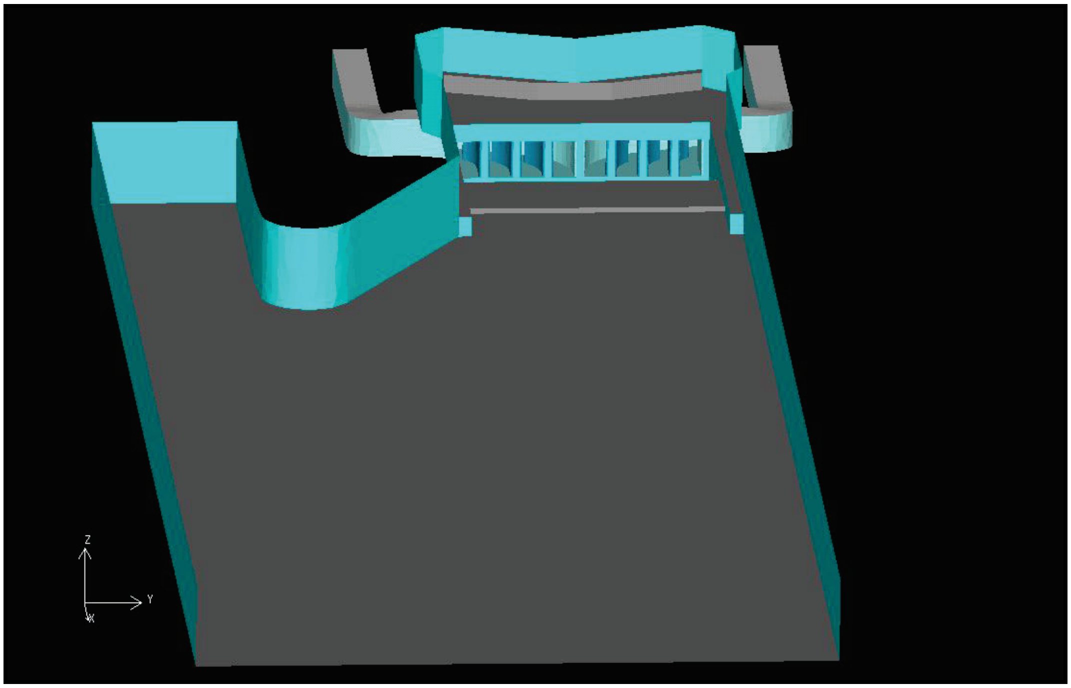


Figure 9. The 3-D computational flow model of Marmet Lock intake, velocity distribution along a plane through the culvert center (Stockstill and Berger 2000).

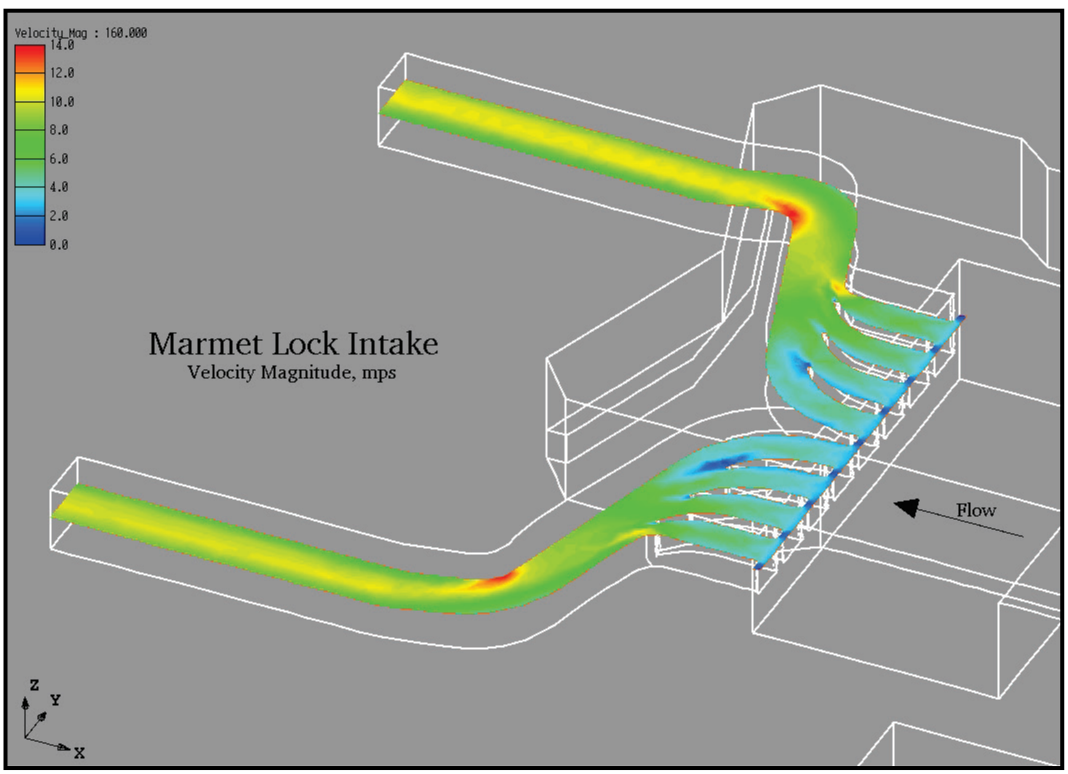
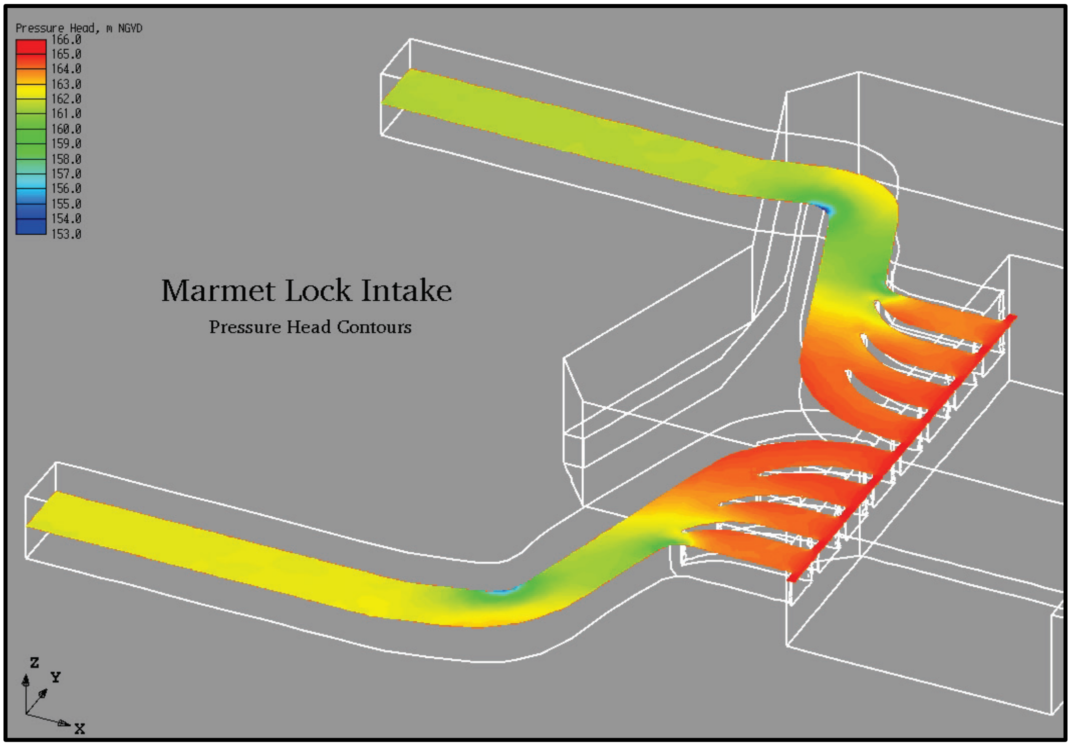


Figure 10. The 3-D computational flow model of Marmet Lock intake, pressure distribution along a plane through the culvert center (Stockstill and Berger 2000).

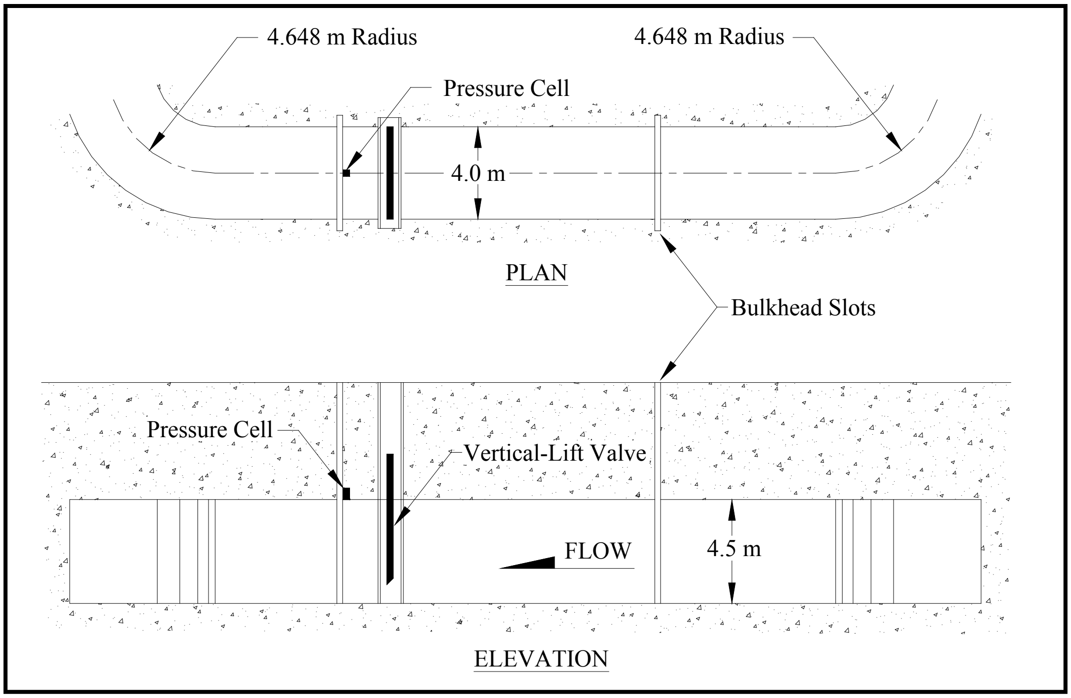


Maximum velocities and minimum pressures occurred along the inside wall of the first culvert bend. The velocity magnitude was about 7 meters per second (m/sec) on the outside wall of the bend and about 14 m/sec along the inside culvert wall (Figure 9). The difference in pressure head across the culvert in the bend was about 10 m. The piezometric elevation was approximately 163 m on the outside and 153 m along the inside culvert wall (Figure 10).

2.2.2 Valve Model

A 3-D computational flow model of one of the Marmet Lock vertical-lift valves (Figure 11) was constructed to evaluate the possibility of reproducing the flow conditions resulting from valve motion during lock filling operations (Scheffermann and Stockstill 2009). Numerical modeling of components that move through the flow domain requires solution of an additional equation. The space conservation law describes the hydrodynamic effects of boundary motion as the valve moves through the flow domain. This additional conservation law, which is solved simultaneously with the RANS equations, relates the change in the cell volume to the valve's reference-frame velocity. The equations were discretized on hexahedral cells that described the flow domain.

Figure 11. Marmet Lock left vertical-lift valve model, pressure cell location (modified from Scheffermann and Stockstill 2009).

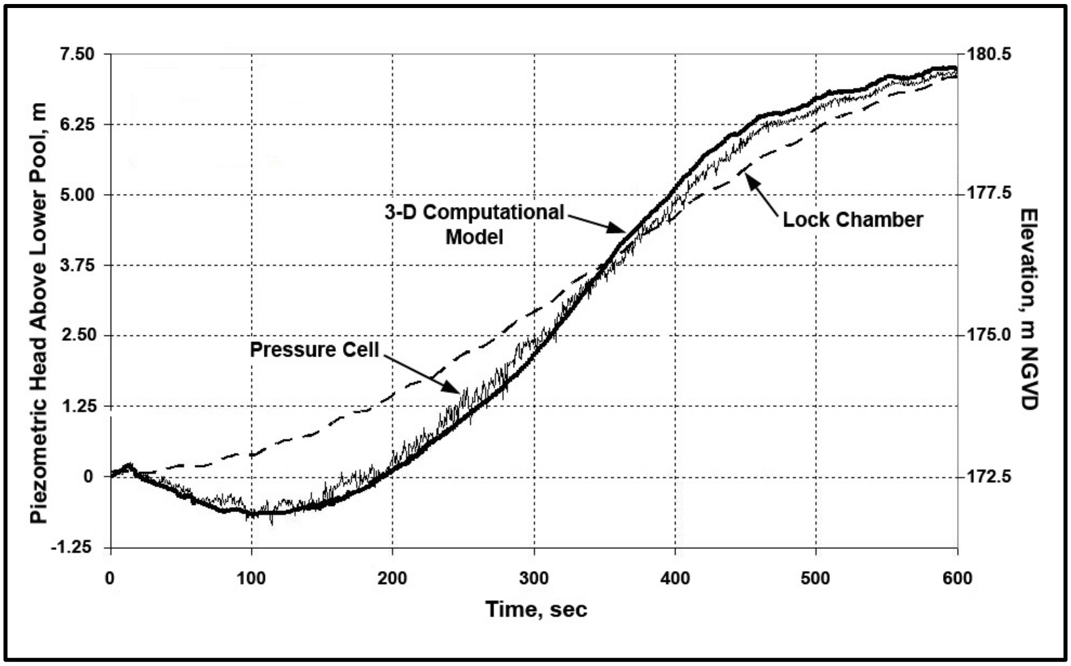


Valve motion was simulated using a moving mesh routine that computed time-varying flow rates and velocity distribution even in complex flow areas such as within the vena contracta. Maximum velocities within the jet, under the vertical-lift valve, were near 18 m/sec when the valve was approximately 60 % open with an 8 min valve speed.

Pressure boundary conditions were specified at the intake and the outlet. The intake pressure was constant, reproducing the water level in the project's upper pool. The outlet pressure was specified as time varying, representing a changing water level in the lock chamber.

Pressures during valve movement with opening speeds of 2, 4, and 8 min were tested in the physical model and simulated in this study. The pressure measured on the culvert roof at a distance approximately one-half a culvert height downstream of the vertical-lift valve showed the pressure development during valve operation. The comparison (Figure 12) showed a good agreement between computed and observed pressures with maximum deviations in the range of 2 %.

Figure 12. Computed and observed pressures downstream of the valve, 8 min valve opening schedule (modified from Scheffermann and Stockstill 2009).



Immediately after the valve began opening, the downstream culvert pressure increased. Quickly thereafter, a relatively high-velocity jet developed beneath the valve, followed by a pressure drop. As the area under the valve increased, the jet velocity decreased and culvert pressure began to rise. The duration of low pressure was longer for a valve opening speed of 8 min than for a 2 or 4 min valve operation. The slower valve operation speed led to a longer time with a relative small flow area, which produced this pressure drop. The low-pressure zone was not sufficiently low enough to indicate cavitation, and the pressures downstream of the valves were never adverse.

3 Field Data

Two separate sets of prototype data were collected at the new Marmet Lock. The first set of tests was conducted in August 2010, and the second set of experiments was performed the following summer, in August 2011. The lock chamber water-surface elevation was measured with pressure transducers installed in the ladder wells in the chamber. Additional pressure gauges recorded the upper and lower pool elevations. Each transducer was labeled to correspond with the lock chamber station at which it was mounted. Locations of the pressure transducers used to measure the lock chamber water-surface elevation are shown in Figure 13. Pressures within the chamber were measured at two locations during the August 2010 experiments: at 50 ft and 750 ft downstream from the upper miter gate pintle (Sta 50 and Sta 750, respectively, in Figure 13). The August 2011 field tests had three transducers mounted in the chamber at 50 ft, 300 ft, and 650 ft downstream from the upper miter gate pintle (Sta 50, Sta 300, and Sta 650, respectively, in Figure 13).

The pressure transducers were sampled every 30 sec continuously for 48 hr during the August 2010 experiments, and every 5 sec continuously for 34 hr during the August 2011 experiments. Both data sets were continuous records of the pressures in the lock from which a variety of lock operations were extracted. The data from the extracted operations were adjusted in time by zeroing the valve initialization time. The operation and river conditions for the field experiments are listed in Table 1. The existing valve operations of the Marmet Lock filling and emptying valves include a closure step that virtually eliminates over-travel. These valve schedules were developed in the field to minimize any reverse head on closed miter gates due over-travel. The reverse head tends to open miter gates. The filling valves are opened in approximately 3 min, held at the open position for about 3 min, and then closed to about 5 ft where they are held until the operation is ended. The emptying valves are operated in a similar manner.

The primary or first mode of oscillation (an end-to-end seiche) is the most important in- lock design. The first mode of oscillation in the chamber, during which the water rocks back and forth, provides the hydrostatic force needed to accelerate a full barge tow. The first mode of oscillation in the lock chamber is the hydraulic force that the mooring lines must hold.

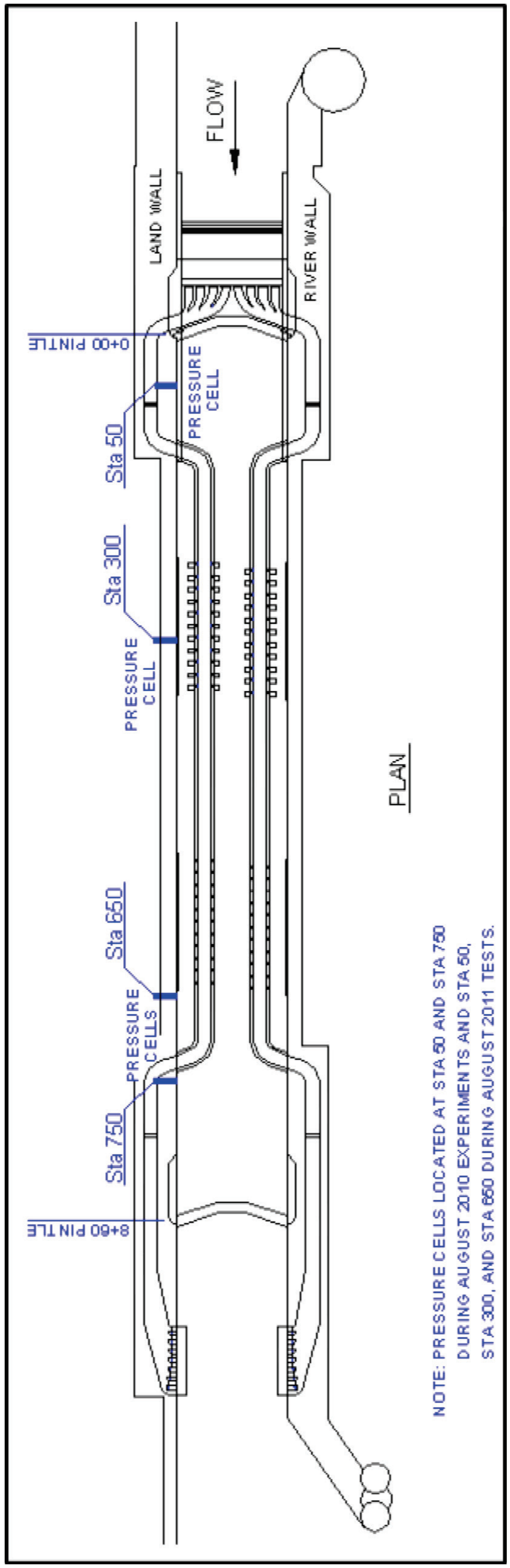


Figure 13. Field data pressure cell locations in the Marmet Lock chamber.

Table 1. Field data collection conditions.

Test	Operation	Upper Pool	Lower Pool	Valve operation
F1	Filling	590.2	566.0	Valves opened to 15.2 ft in 183 sec
F2	Filling	590.2	566.0	Valves opened to 15.2 ft in 183 sec
F3	Filling	590.2	565.8	Valves opened to 15.2 ft in 188 sec, then 192 sec later, valve closed to 5.4 ft in 78 sec
F4	Filling	589.6	566.1	Single 4 min valve (river wall culvert)
E1	Emptying	590.3	566.0	Valves opened to 15.2 ft in 176 sec, then 192 sec later, valve closed to 5.9 ft in 78 sec
E2	Emptying	590.5	566.3	Valves opened to 15.2 ft in 176 sec, then 192 sec later, valve closed to 5.9 ft in 78 sec
E3	Emptying	590.2	566.0	Valves opened to 15.2 ft in 176 sec, then 192 sec later, valve closed to 5.9 ft in 78 sec

Higher modes, such as those generated as the miter gates close, tend to affect smaller craft, but do not exert a measureable hydrodynamic force on a loaded barge train (McNown 1967). Estimation of hawser forces is beyond the scope of the present study. It is difficult to determine the lock-chamber water-surface slope using point pressure measurements. Identification of an end-to-end slope requires that numerous synchronized pressures located along the length of the chamber show that the water surface is planar. Estimation of the longitudinal hawser force as a product of the water-surface slope and the tow's weight necessitates that the entire barge train is parallel to the water-surface slope.

4 Numerical Model

4.1 Model Description

This study's principal objective was to construct a computational flow model of the Marmet Lock system, validate its accuracy by comparison with field data, and evaluate the hydraulic performance at the design lift of 24 ft. The numerical flow model LOCKSIM (Schohl 1999) serves as an evaluation tool for lock filling and emptying system designs. The model computes pressures and flow distributions throughout a lock system. LOCKSIM couples the unsteady pressure-flow equations (which are applicable to the conduits within the system) with the free-surface equations (which describe the approach reservoirs and lock chamber). Individual components are connected together at nodes where they share a common piezometric head.

A schematic illustrating the nodes and components of the LOCKSIM model is provided in Figure 14. The numerical model reproduced the entire filling and emptying system including the intakes, filling and emptying valves, culverts, filling and emptying manifolds, lock chamber, and outlets. Discharge and piezometric head in the culvert and free-surface channel components are computed by numerically solving partial differential equations for 1-D unsteady flow. The relationships between discharge and piezometric head for component losses are described by algebraic energy equations. The time-dependent position of a valve can be prescribed using tabulated data. Functions are used for manifold components to describe the variation of branch head-loss coefficient with the port-to-culvert discharge ratio. Solutions include time-varying pressure and energy grade-line elevation at all computational nodes, and discharge and velocity at all computational components.

4.2 Model Parameters

Numerical model parameters such as the time step and the implicit weighting factor used in the Preissmann's scheme (Schohl 1999) were selected based on previous LOCKSIM studies (Stockstill et al. 2001; Stockstill 2002). Lock filling and emptying simulations employed a time step of 2.0 sec, and an implicit weighting factor of 0.7 provided sufficient stability.

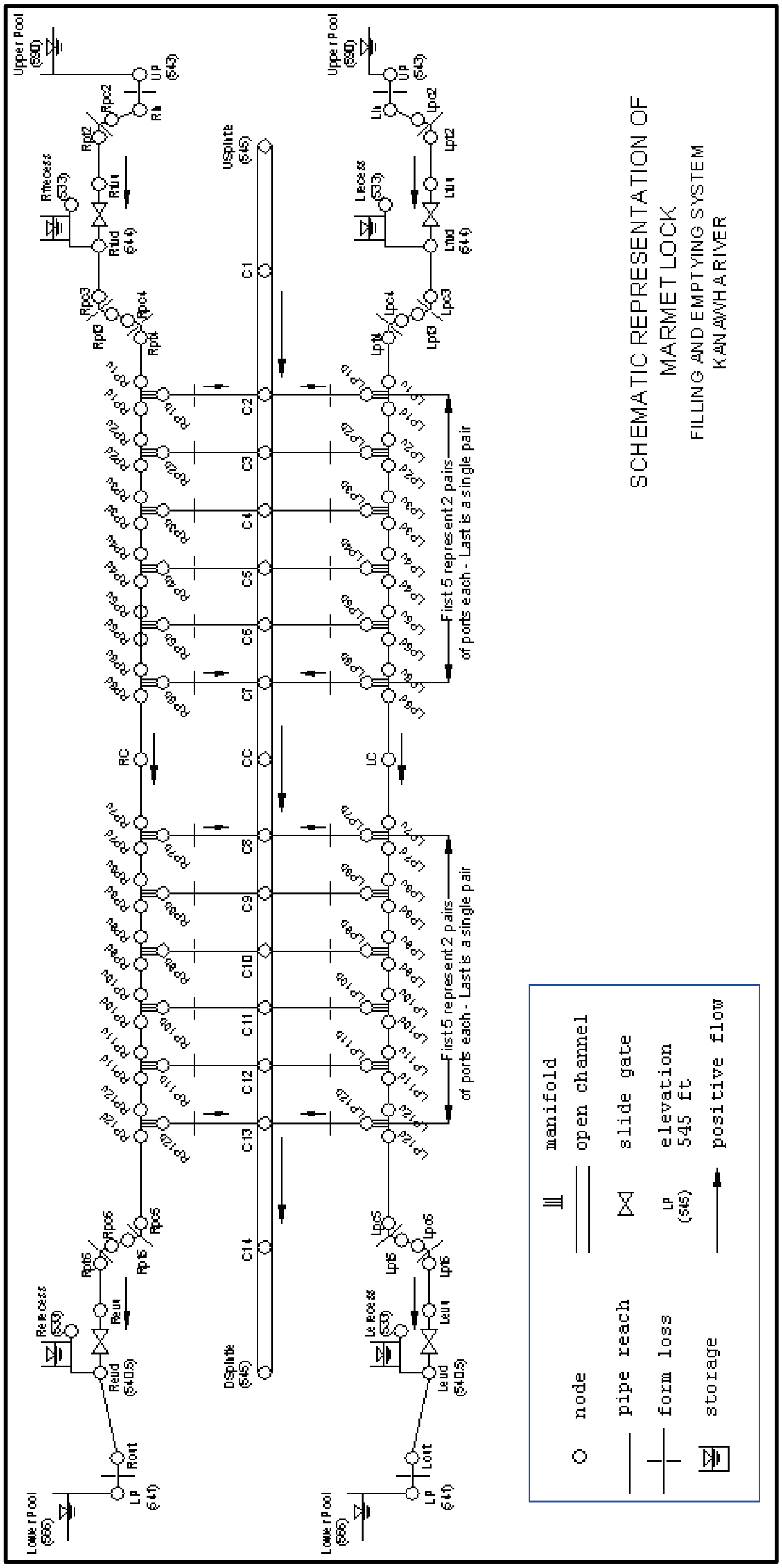


Figure 14. Numerical model schematic of Marmet Lock culvert system.

4.3 Hydraulic Coefficients

The energy loss, H_{L_i} through each component can be expressed as:

$$H_{L_i} = K_i \frac{V_i^2}{2g} \tag{1}$$

where:

K_i = loss coefficient for component i
V_I = the velocity through component i

Loss coefficients for many hydraulic components are well established and are readily available in the literature (Miller 1990). However, lock culvert system components are often unique to a particular project, and the loss coefficients have not been determined. This study validated the LOCKSIM model using field data to refine loss coefficient values. These coefficients were then used in modeling design conditions, and to investigate prototype hydraulic conditions with existing valve operations at the design lift.

Energy loss coefficients for flow through the intakes were taken from the previous physical model study (Hite 1999). Manifold port loss coefficients came from the In-chamber Longitudinal Culvert System (ILCS) study (Hite and Stockstill 2003). Loss coefficients for the right culvert of the Marmet Lock LOCKSIM model are provided in Tables 2 and 3 for the lock filling and emptying system, respectively. Loss coefficients for the right and left culverts were identical.

The head loss as flow passes a partially-opened vertical-lift valve varies during a valve operation because the loss is a function of the shape of the valve lip and the valve opening. The efficiency of the vertical-lift valves is commonly described in the literature as a head-discharge relationship rather than in terms of head loss across the valve. The head-discharge relation is expressed empirically with a discharge coefficient, C_V, which is defined as:

$$C_V = \frac{Q}{bW\sqrt{2g\,H_V}} \tag{2}$$

where:

Q = discharge
b = valve opening

W = valve width
H_V = differential head across the valve

Table 2. Loss coefficients for filling system.

Right Culvert			
Lock Component	**Upstream Node**	**Downstream Node**	**Loss Coefficient, *K***
Intake Manifold	UP	Rin	0.12
Bend	Rpc2	Rpt2	0.16
Bend	Rpc3	Rpt3	0.16
Bend	Rpc4	Rpt4	0.16
Filling Ports	RP1b RP2b RP3b RP4b RP5b RP6b RP7b RP8b RP9b RP10b RP11b RP12b	C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13	Outflow K = 0.10 Inflow K = 1.25

Table 3. Loss coefficients for emptying system.

Right Culvert			
Lock Component	**Upstream Node**	**Downstream Node**	**Loss Coefficient, *K***
Emptying Ports	RP1 RP2 RP3 RP4 RP5 RP6 RP7 RP8 RP9 RP10 RP11 RP12	C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13	Outflow K = 0.10 Inflow K = 15
Bend	Rpc5	Rpt5	0.16
Bend	Rpc6	Rpt6	0.16
Outlet Manifold	Rout	LP	1.13

Discharge coefficients for vertical-lift valves are provided in the Hydraulic Design Chart 320-1 (Headquarters, U.S. Army Corps of Engineers 1988). The relation between the discharge coefficient and a head loss coefficient for the valve, K_V, can be determined by equating the change in head across the valve in Equations (1) and (2). Thus, it follows that:

$$K_V = C_V^{-2} \tag{3}$$

Given the field data, physical model data, two 3-D computational flow models, and the current LOCKSIM models, general hydraulic information of the Marmet Lock system was determined. Hydraulic coefficients of the filling and emptying system components were determined from the various models and field data. These parameters were developed for an In-chamber Longitudinal Culvert System (ILCS), of which Marmet Lock is only the second such system to have been constructed. The other system is the new McAlpine Lock on the Ohio River, which opened April 2009.

4.4 Pressure Distribution within the First Bend

Flow in a bend of a rectangular culvert is characterized by high velocities and low pressures on the inside wall of the culvert bend, and lower velocities and higher pressures along the outside wall. Pressures on the inside wall of a culvert bend can be estimated from the cross-sectional average velocity and pressure within the culvert (Headquarters, U.S. Army Corps of Engineers 1988) as:

$$h_{pi} = h_p - C_p \frac{V^2}{2g} \tag{4}$$

where:

h_p = cross-sectional average pressure head
h_{pi} = pressure head on the inside of the bend
C_p = pressure drop coefficient
V = cross-sectional average velocity

The pressure coefficient, C_p, is a function of the culvert curvature (Hydraulic Design Chart 228-3, Headquarters, U.S. Army Corps of Engineers 1988). The 3-D computational flow model results from Stockstill and Berger (2000) were used to determine the pressure

coefficient for the horizontal bend upstream of the valve. Continuity dictates that with a discharge of 305 cubic meters per sec (m^3/sec), the culvert velocity was 16.9 m/sec, which corresponds to a velocity head of 14.6 m. The pressure head difference between the cross-sectional average and that at the inside of the bend was 5.0 m. Using Equation (4), C_p for the culvert bend was found to be 0.34. That is, the pressure head difference between the cross-sectional average and that on the inside of the bend is about 34 % of the average velocity head in the culvert. This information was used with the LOCKSIM design conditions results to examine the low pressure along the inside wall of the first bend.

5 Existing Field Conditions

The valve operation schedules listed in Table 1 for Tests F3 and E1 are the manner in which the valves are normally operated. These schedules, which begin valve closure as the lock chamber water-surface elevation approaches the final value, were developed in the field to minimize over-travel.

5.1 Operation Conditions

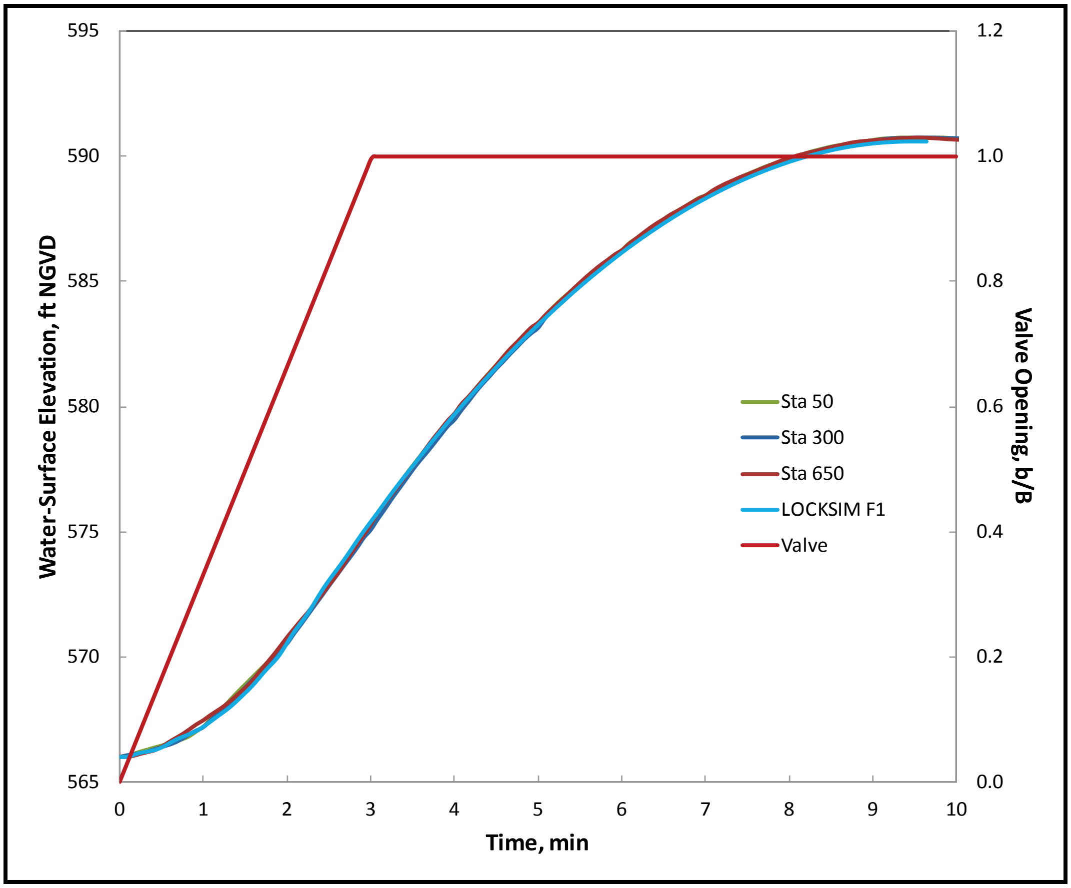
Operation conditions presently used at the project were modeled to evaluate the existing hydraulic conditions throughout the system. The river conditions and valve operations used during the field experiments (Table 1) were simulated. The valve operation times of 180 sec for both the filling and emptying valves were supplied by operation personnel. Both normal- (dual-) and single-valve filling and emptying operations were modeled.

The filling curves for Test F1 and the emptying curves for Test E1 were used to adjust coefficients in the numerical model. The resulting coefficients were then used to model the remaining field data conditions (Tests F2-F4, and Tests E2 and E3). Once the valve coefficients and system parameters were chosen, the only changes made to the LOCKSIM models were the pool elevations and the valve opening position versus time.

5.2 Filling Operations

Filling operations for Test F1 through Test F4 conditions (Table 1) were simulated. The results of these calculations are shown on the time history plots in Figures 15-18. Test F1, F2, and F3 were part of the field data obtained in August 2011, where three pressure cells were mounted in the chamber at Sta 50, Sta 300, and Sta 650 (Figure 13). Test F4 data were from the set taken during the August 2010 field experiments, where two pressure cells were mounted in the lock chamber at Sta 50 and Sta 750 (Figure 13).

Figure 15. Test F1 field data and numerical model results, 3 min normal-valve filling, upper pool el 590.2, lower pool el 566.0.



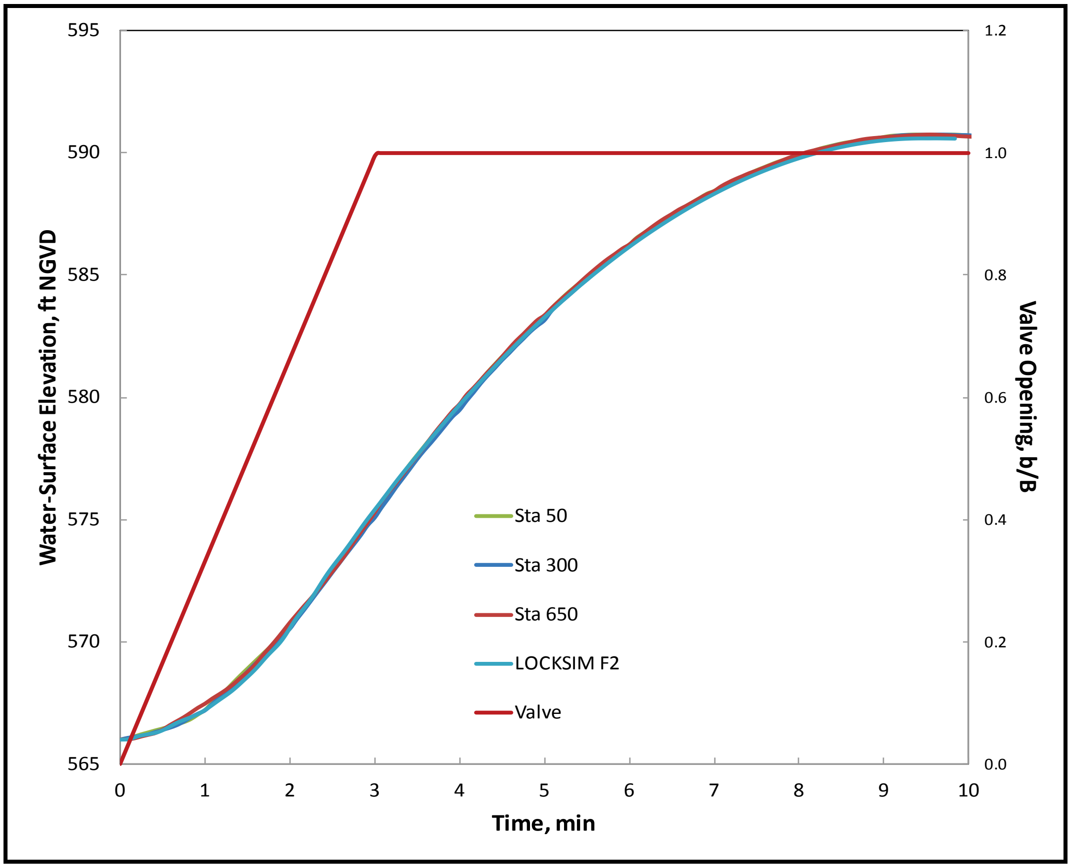
5.2.1 Test F1 Conditions

Simulations with the Test F1 conditions (Table 1) were conducted. The river conditions were an upper pool el 590.2 and lower pool el 566.0. Normal-valve operations consisted of the vertical-lift valves opening at an assumed constant rate in 183 sec, which meant that the valve lip reached the culvert soffit of the 15 ft high culvert in 181 sec. The simulation results, showing the valve-opening curve and fill curve, are plotted with the field data in Figure 15.

5.2.2 Test F2 Conditions

Test F2 conditions were identical to those of Test F1. However, Test F2 provided a chance to look at the variability of the field data from experiment-to-experiment. LOCKSIM results of valve-opening curve and fill curve are provided in Figure 16. Test F2 field data were consistent with those of Test F1, and the numerical model accurately reproduced the lock chamber water-surface elevations (fill curves).

Figure 16. Test F2 field data and numerical model results, 3 min normal-valve filling, upper pool el 590.2, lower pool el 566.0.

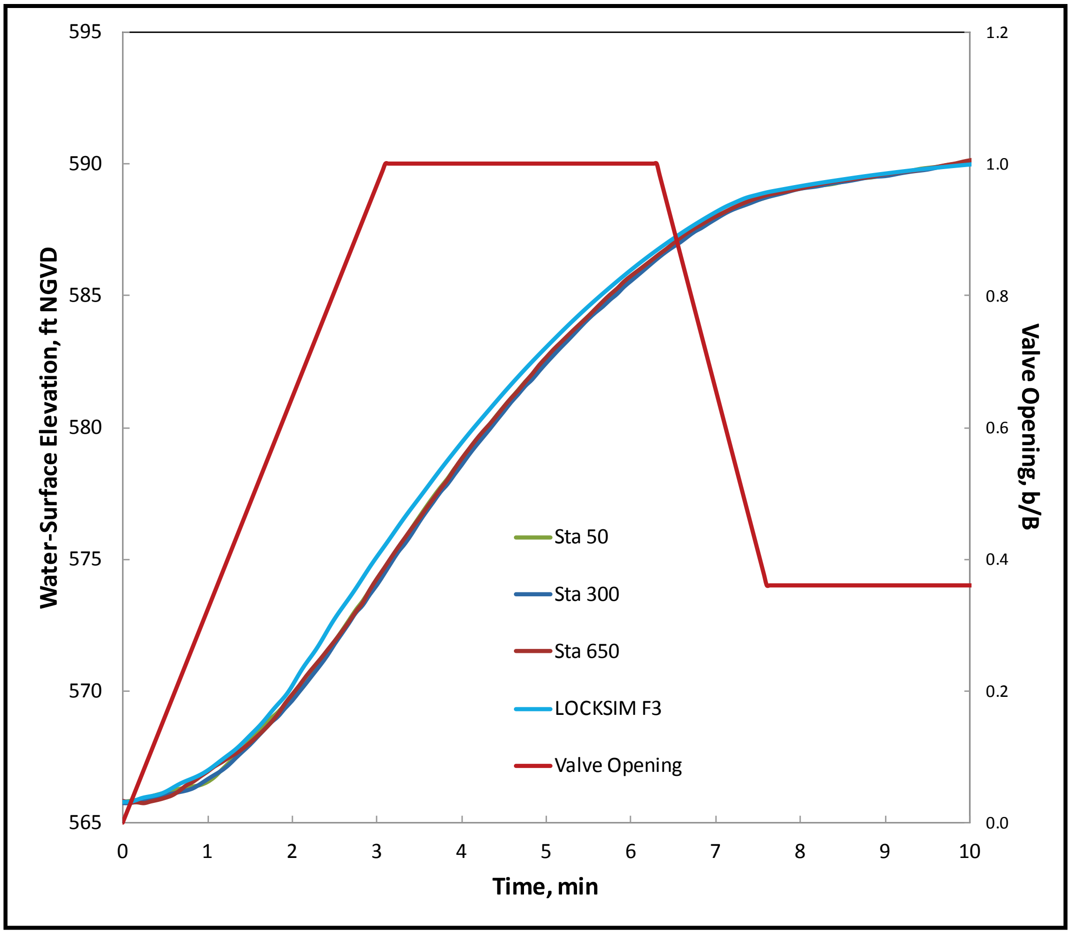


5.2.3 Test F3 Conditions

Test F3 river conditions differed from the first two filling tests in that the lower pool had dropped 0.2 ft to el 565.8. As mentioned previously, the valve schedule for Test F3 included valve closure as the lock chamber water-surface approached the upper pool elevation. The fill valves were raised to fully opened position, held at this position for a particular time, and then lowered to approximately 40 % open. Details of this valve operation pattern are provided in Table 1. The valve-opening curve and the LOCKSIM results are shown in Figure 17. The water-surface elevation did not match the field data as well as the first two tests; the computed results had the lock filling faster than the field data during the time between 2 and 4 min. Specifically, at 3 min into the filling operation, the computed lock chamber water-surface elevation was 0.9 ft higher than the observed average. The LOCKSIM model computed the chamber water-surface to be el 575.1, whereas the average of the field data at this time was el 574.2. However, the simulation reproduced the observed data at the time when the valve closure

was used to slow the filling rate (6 min). These data illustrate that the valve operation essentially prevents over-fill.

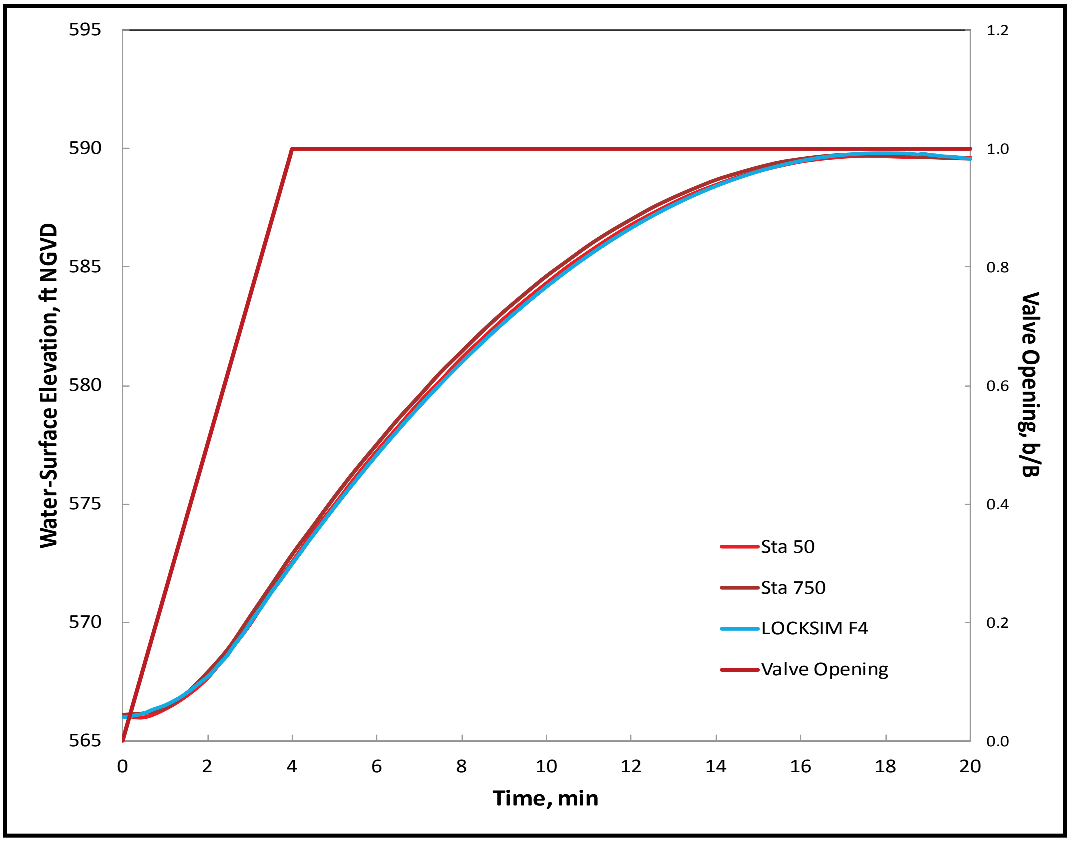
Figure 17. Test F3 field data and numerical model results, 3 min normal-valve filling, upper pool el 590.2, lower pool el 565.8.



5.2.4 Test F4 Conditions

Test F4 was a filling operation that used a 4 min single-valve schedule, wherein the river-wall culvert valve was opened. The river conditions of an upper pool el 589.6 and lower pool el 566.1 resulted in a 23.5 ft lift. Filling curves from the field data are shown in Figure 18 along with the LOCKSIM results. The LOCKSIM model accurately reproduced the time-varying field data. The numerical model computed the fill time to be 16.3 min, and the field data, which were only sampled every 0.5 min, showed that the water-surface reached the upper pool elevation sometime between 16.0 and 16.5 min. The largest differences shown on the fill curves in Figure 18 are between the two field data pressure cells. The numerical model reproduced the fill time of the single valve operation reasonably well.

Figure 18. Test F4 field data and numerical model results, 4 min single-valve filling, upper pool el 589.6, lower pool el 566.1.



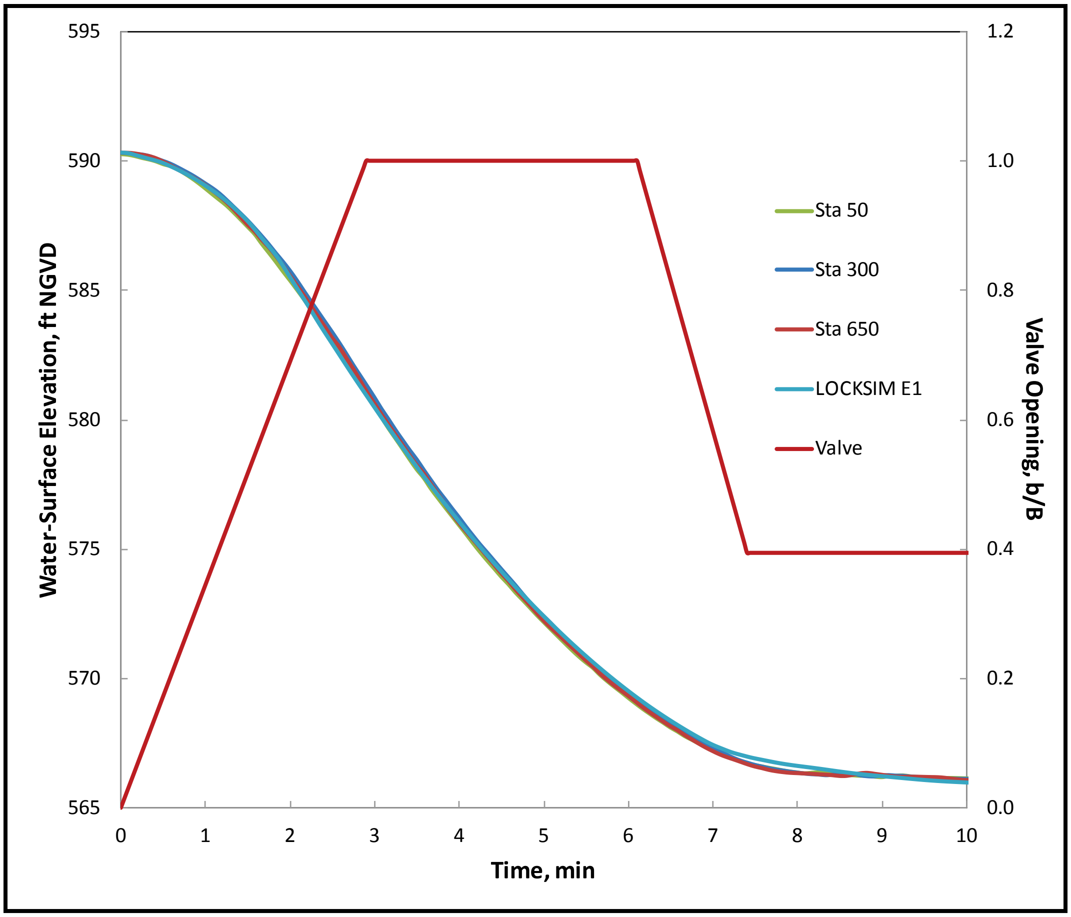
5.3 Emptying Operations

Simulation of flow conditions during lock emptying were made for the existing field conditions listed in Table 1. Field data and the numerical model results of the emptying operation are shown in Figures 19-21. Each of these emptying operation experiments (E1, E2, and E3) were part of the field data obtained in August 2011, where three pressure cells were mounted in the chamber at Sta 50, Sta 300, and Sta 650 (Figure 13).

5.3.1 Test E1 Conditions

LOCKSIM results for a 3 min normal-valve emptying operation with an upper pool el 590.3 and lower pool el 566.0 are shown in Figure 19, as well as the valve schedule and the emptying curves. The largest difference in the computed and observed lock-chamber water-surface elevation was at about 8 min into the operation when the LOCKSIM results were 0.2 ft higher than the observed valve. At 8 min the computed water-surface was el 566.6 and observed water surface averaged el 566.4.

Figure 19. Test E1 field data and numerical model results, 3 min normal-valve emptying, upper pool el 590.3, lower pool el 566.0.



5.3.2 Test E2 Conditions

LOCKSIM results for the Test E2 conditions are provided in Figure 20. The emptying curves show that during the first half of the operation, the numerical model filled faster than the observed rate. The largest difference in the computed and observed lock chamber water-surface elevation occurred at about 2.5 min into the operation at which time the computed value was el 583.1 whereas the field data averaged el 584.1. The model led the field data by 1.0 ft at 2.5 min after emptying had begun.

5.3.3 Test E3 Conditions

The computational model results for the Test E3 conditions are provided with the field data on the emptying curves in Figure 21. The results of this simulation are similar to Test E2. There was a 1.3 ft error at about 3 min into the emptying operation. At 3 min the computed water-surface was el 580.4 and the average valve for the field data was el 581.7. However,

pressure cell readings within the chamber differed by 0.9 ft at this same time. The field data suggested that the highest point on the lock chamber water surface was at the chamber center (el 582.2 at Sta 300), and that the lowest point was at the downstream end (el 581.3 at Sta 650).

Figure 20. Test E2 field data and numerical model results, 3 min normal-valve emptying, upper pool el 590.5, lower pool el 566.3.

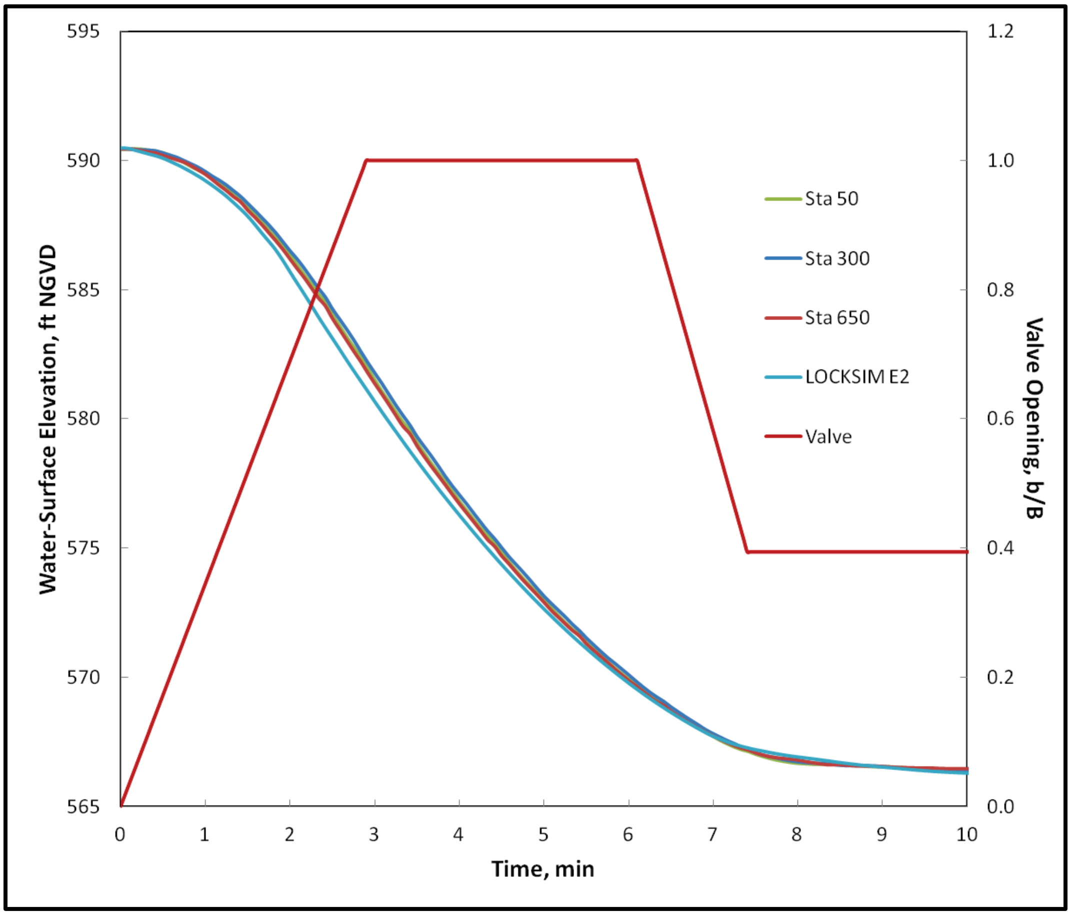
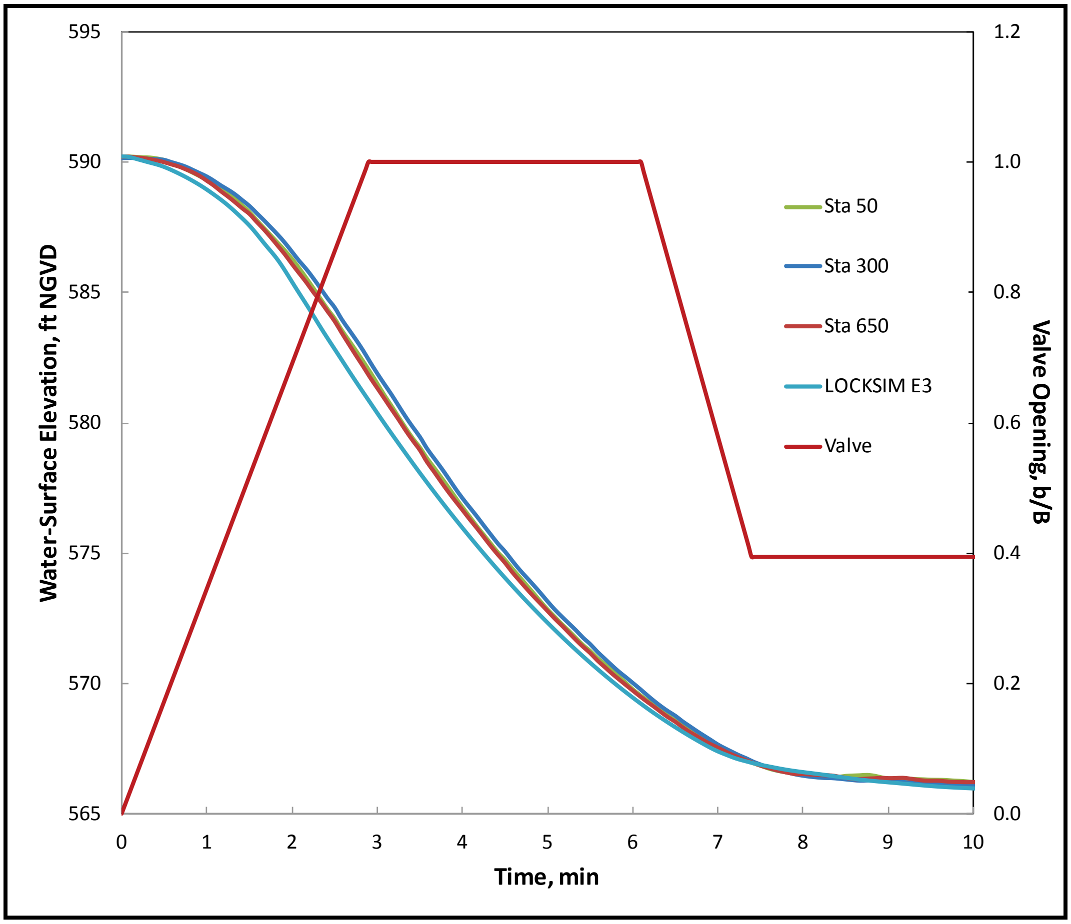


Figure 21. Test E3 field data and numerical model results, 3 min normal-valve emptying, upper pool el 590.2, lower pool el 566.0.



6 Design Conditions

The numerical model was used to evaluate the hydraulic performance during locking operations at the project's design conditions. Design conditions are a 24 ft lift with an upper pool el 590 and a lower pool el 566. The time required to fill and empty the lock, along with velocity and pressure distribution throughout the filling and emptying system were calculated. Both lock filling and emptying operations, each with normal- and single-valve schedules, were simulated.

The valves were opened in 3 min during normal-valve operations and 4 min during single-valve operations. Each of the design condition simulations had the valve raised in the prescribed time and held open for the remainder of the operation. So, the design condition simulations differed from the existing field operations in that they allowed over-travel, whereas the field operations avoided over-travel by partially closing the valves near the end of the locking operation.

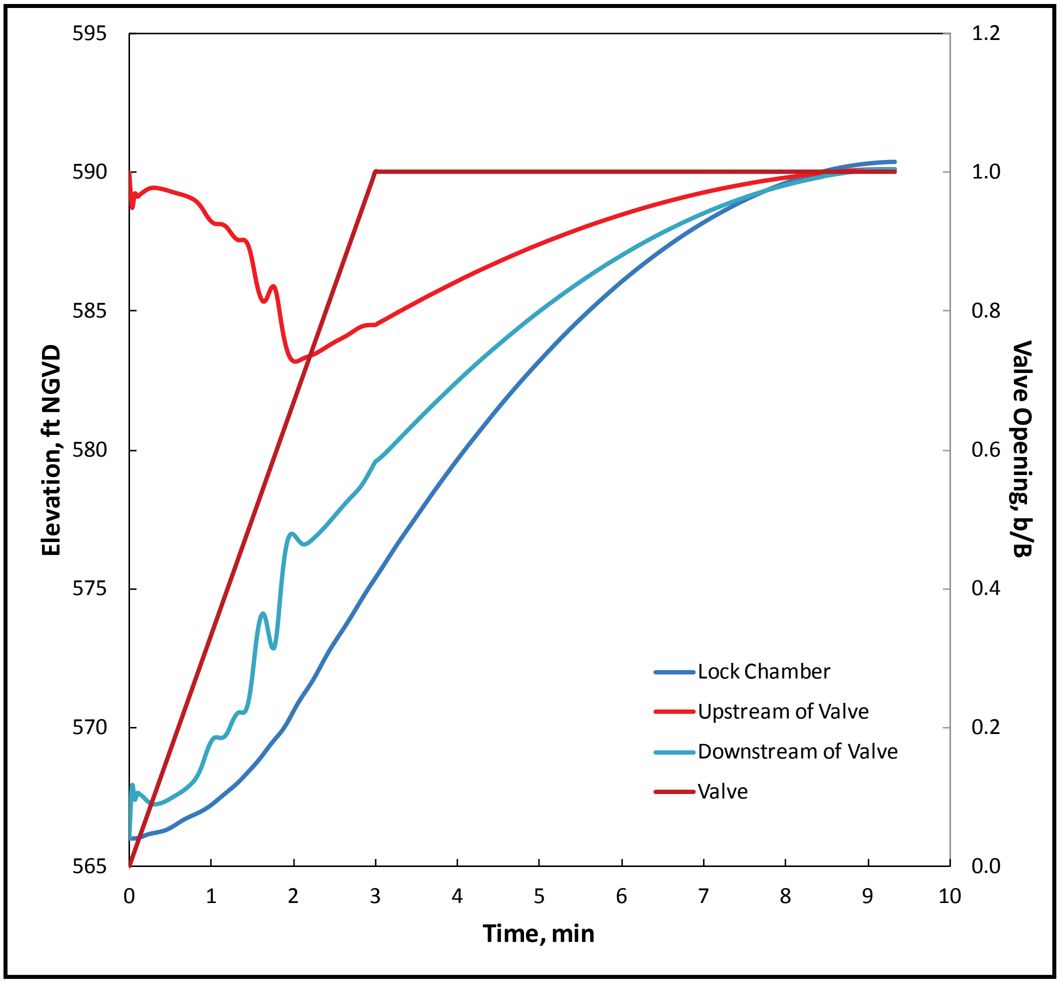
6.1 Filling Operations

The filling operation was simulated to determine the lock filling time, discharge, pressures, and velocities in the culvert.

6.1.1 Normal-Valve Operations

The simulation results for a normal-valve operation, where the synchronized valves are opened in 3 min, are shown in Figure 22. This figure illustrates the lock chamber water-surface elevation along with the pressure head upstream and downstream of a filling valve. The lock filled in 8.4 min and continued until it had over-filled 0.4 ft. Figure 23 shows the variation of discharge and velocity in each culvert. The peak discharge was 3,430 cubic feet per second (ft^3/sec) per culvert, which by continuity corresponds to a maximum culvert velocity of 17.6 feet per second (ft/sec). These peak values occurred at 130 sec after valve operation was initiated.

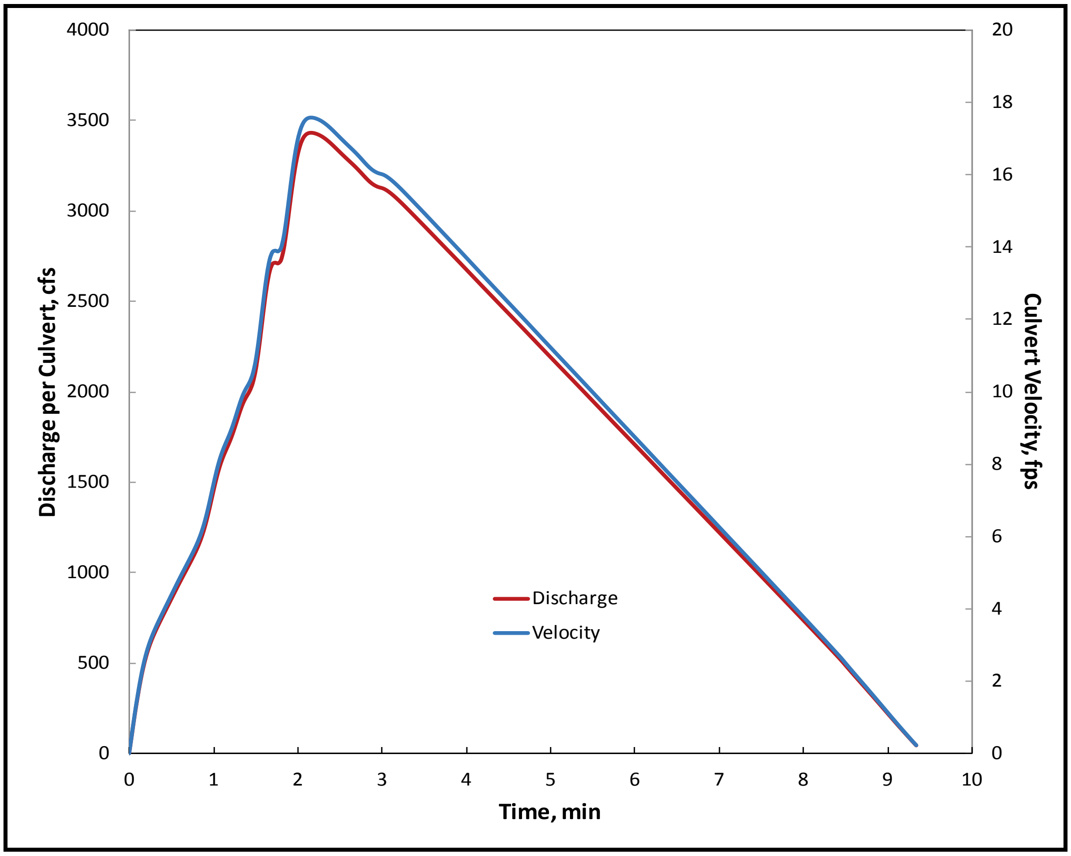
Figure 22. Pressure head in the culverts during normal-valve filling, 3 min valve time, upper pool el 590, lower pool el 566.



6.1.2 Single-Valve Operations

When a single valve is used to fill the lock, such as when one filling valve is out of operation for maintenance or repair, the operating valve is opened in 4 min. The results for a single-valve filling operation are shown in Figures 24 and 25. The single-valve filling curve of Figure 24 shows the rising lock chamber water surface. The valve position as a function of time is also plotted on Figure 24. The pressure head upstream and downstream of the operating valve remained positive (Figure 24). The lock filled in 16.4 min and continued until it had over-filled 0.2 ft.

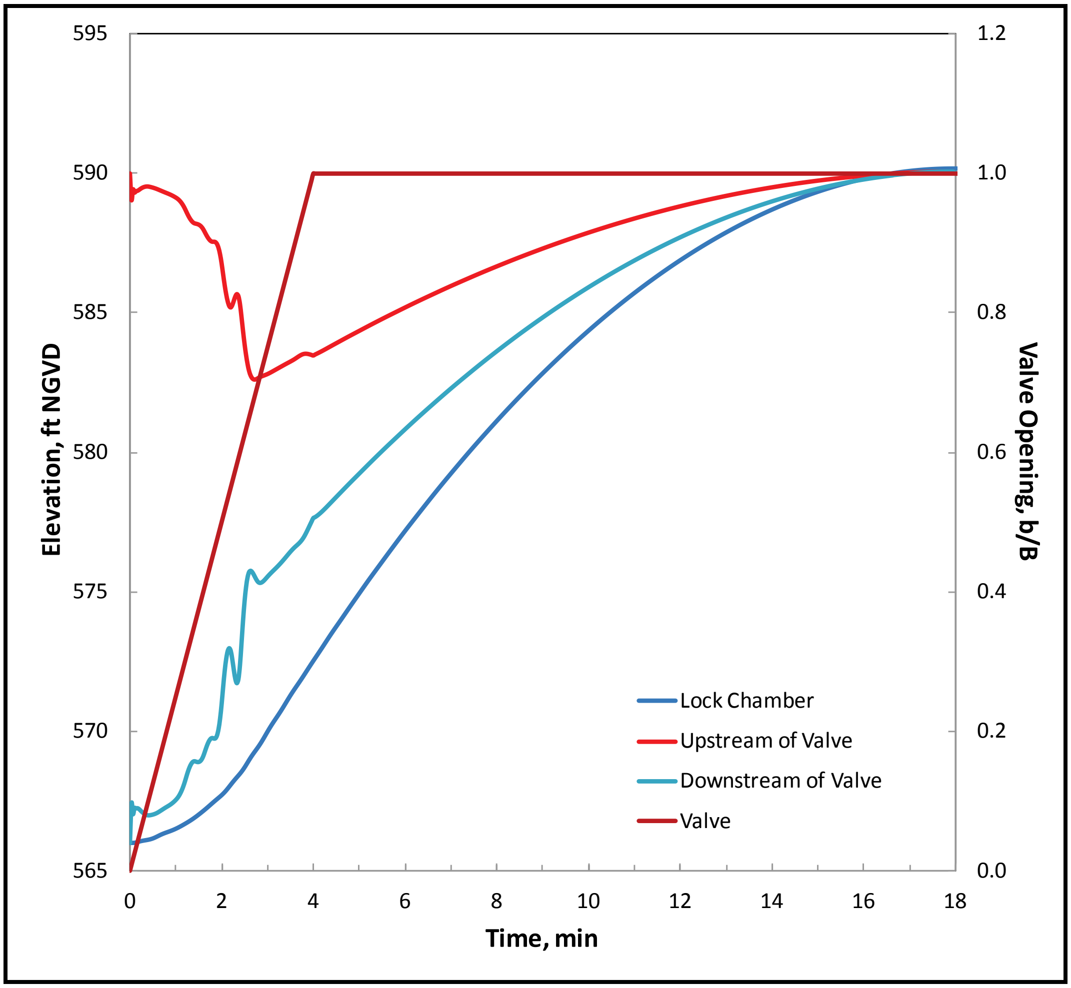
Figure 23. Culvert discharge and velocity during normal-valve filling, 3 min valve time, upper pool el 590, lower pool el 566.



There are two particular reasons why a single-valve operation filled slower than when a normal-valve schedule is used. The obvious reason is because a single culvert has one-half the flow area of two culverts. A second reason is because the single-valve schedule opened the valve in 4 min and a normal-valve schedule opened in 3 min. The slower single-valve speed is used to ensure safe lock chamber conditions. The single-valve filling time of 16.4 min was slightly less than twice the normal-valve filling time of 8.4 min.

Flow rate variation during a single-valve filling operation is illustrated by the discharge graph of Figure 25. Maximum discharge with a single valve occurred at 2.8 min into the filling operation when the discharge was 3,600 ft^3/sec and the velocity was 18.4 ft/sec. The peak discharge when a single valve is used to fill the lock is 5 % larger than the peak discharge per culvert when a normal valve is used (3,600 vs. 3,430 ft^3/sec per culvert). These peak values with the normal-valve schedule occurred at 2.2 min after valve operation was initiated. Peak values with the single-valve schedule occurred at 2.8 min, more than one-half minute later compared to normal-valve operations.

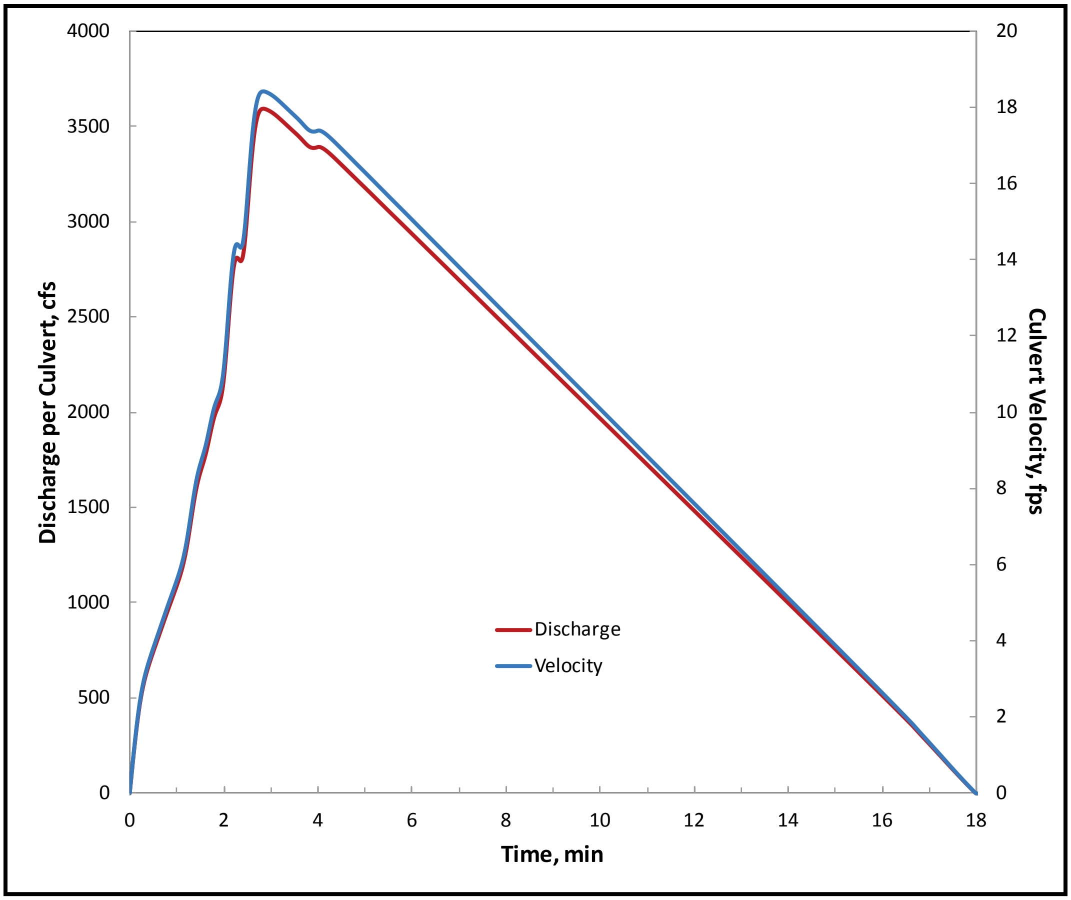
Figure 24. Pressure head in the culverts during single-valve filling, 4 min valve time, upper pool el 590, lower pool el 566.



6.1.3 Pressure on Inside of Culvert Bend

The pressure coefficient, C_p, for the culvert bend upstream of the filling valves was found to be 0.34 in Part 4 of this report (Pressure Distribution within the First Bend). The LOCKSIM model determined that average culvert velocity peaked at 17.6 fps during a normal-valve filling operation which corresponds to a velocity head of 4.8 ft. The pressure on the inside of the bend upstream of the filling valve was estimated using Equation (4) to be 1.6 ft lower than the average pressure. Pressures in the culvert bend during normal-valve filling are plotted in Figure 26. The minimum pressure head on the inside wall of the culvert was el 582.4 and occurred 2.1 min into the filling operation.

Figure 25. Culvert discharge and velocity during single-valve filling, 4 min valve time, upper pool el 590, lower pool el 566.

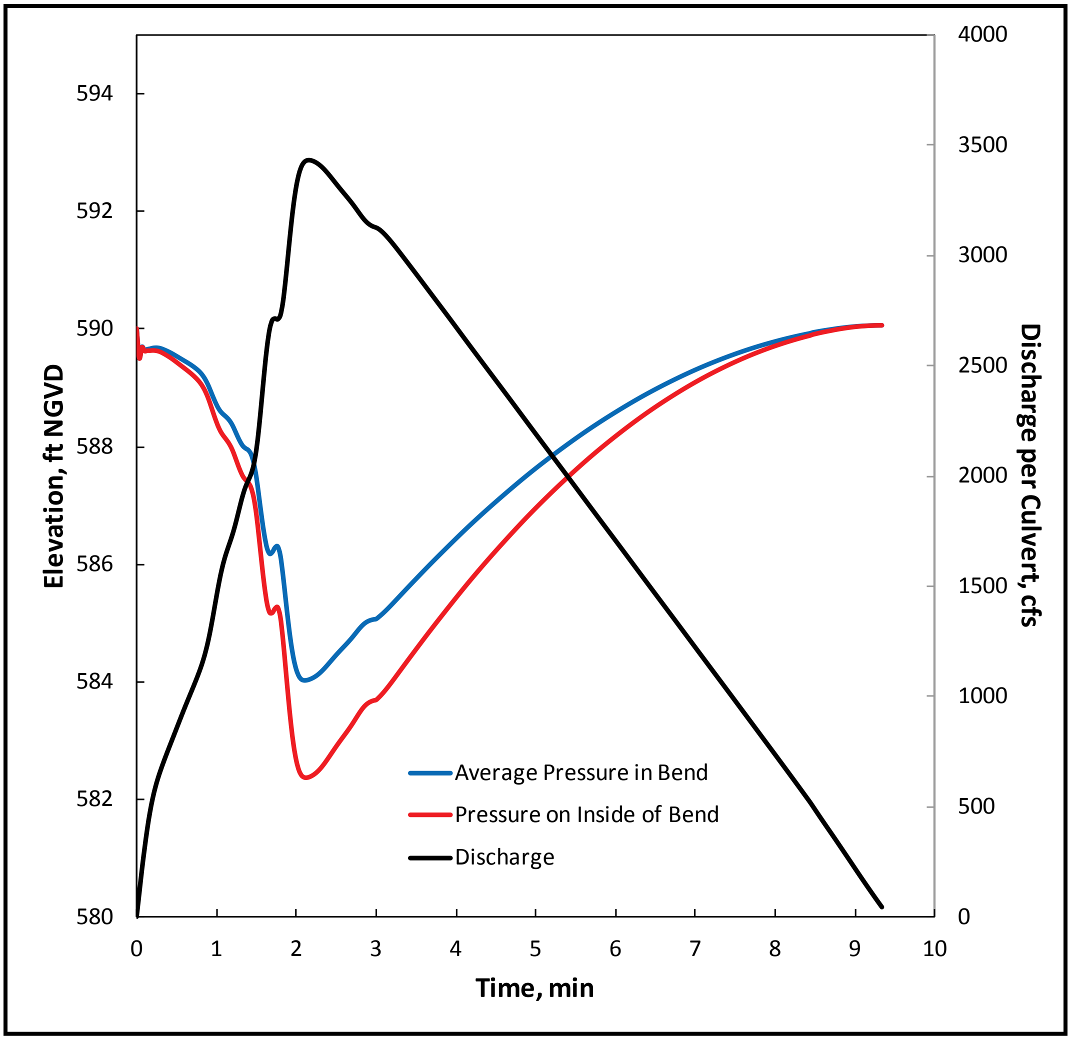


The peak velocity during a single-valve filling was 18.4 ft per sec which corresponds to a velocity head of 5.3 ft. The pressure on the inside of the bend was estimated using Equation (4) to be 1.8 ft lower than the cross-sectional average pressure. Pressures within the culvert bend during a single-valve filling operation are plotted in Figure 27. The lowest pressure head, el 581.6, occurred along the inside wall of the bend at 2.8 min after filling was initiated. The pressures on the inside of the bend during normal- or single-valve filling operations were not sufficiently low to indicate that separation or cavitation could be a problem.

6.2 Emptying Operation

The field experiments found that the emptying valves were operated in a manner similar to the filling valves. The emptying valves were opened in 3 min when normal-valve operations are conducted and were opened in 4 min during single-valve operations.

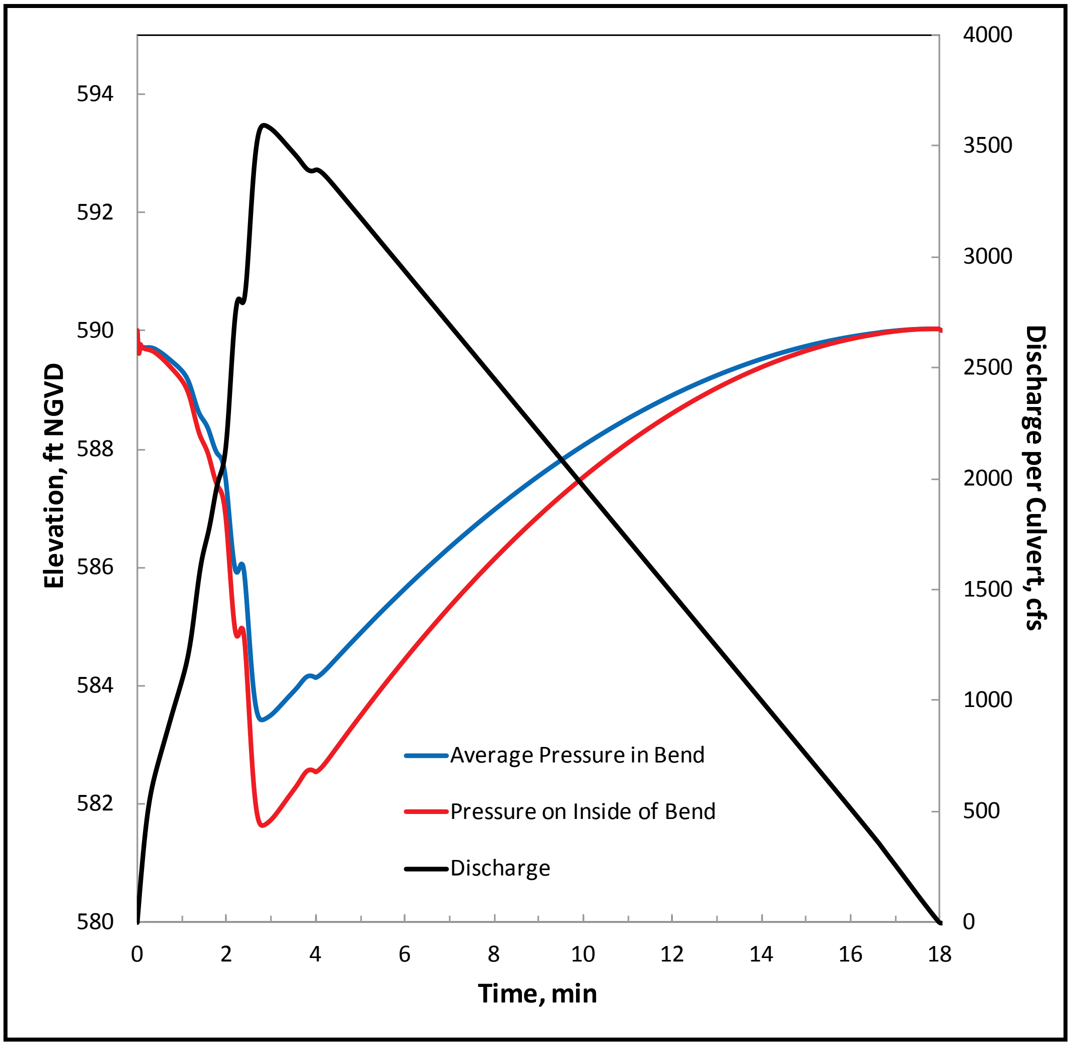
Figure 26. Pressures and discharge in first bend during normal-valve filling, 3 min valve time, upper pool el 590, lower pool el 566.



6.2.1 Normal-Valve Operations

The emptying curve shown in Figure 28 illustrates that during normal-valve operations, the lock emptied in 8.0 min and continued until it had over-emptied 0.5 ft. A maximum discharge of 3,540 ft^3/sec per culvert and velocity of 18.2 ft/sec occurred 2.2 min into the emptying operation (Figure 29).

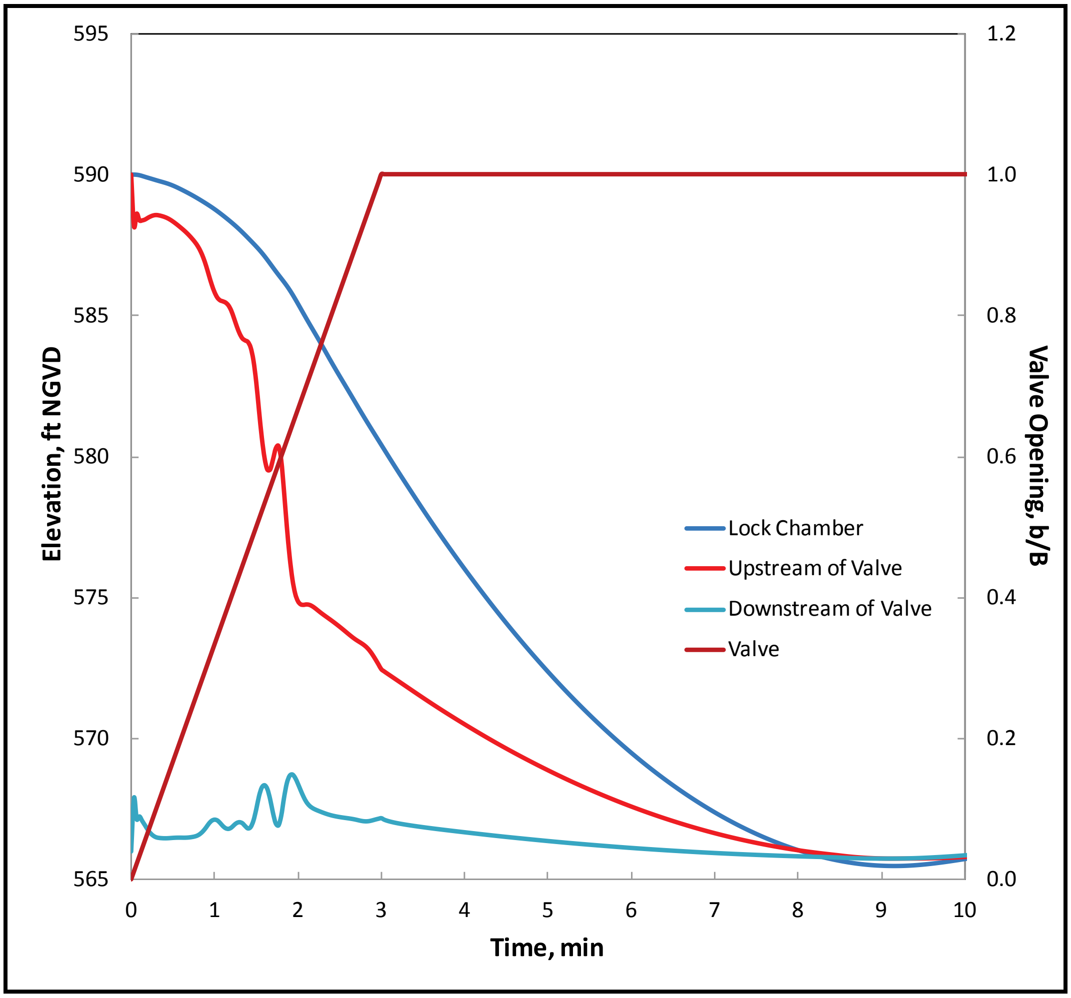
Figure 27. Pressures and discharge in first bend during single-valve filling, 4 min valve time, upper pool el 590, lower pool el 566.



6.2.2 Single-Valve Operations

A single valve is used to empty the lock when one emptying valve is out of operation for maintenance or repair. When the lock was emptied using a single valve, the lock emptied in 15.7 min and over-emptied 0.3 ft (Figure 30). A peak discharge of 3,720 ft^3/sec occurred at 2.9 min into the emptying operation (Figure 31). This discharge which corresponds to a maximum culvert velocity of 19.1 ft/sec is 5 % larger than the peak discharge with a normal-valve operation.

Figure 28. Pressure head in the culverts during normal-valve emptying, 3 min valve time, upper pool el 590, lower pool el 566.

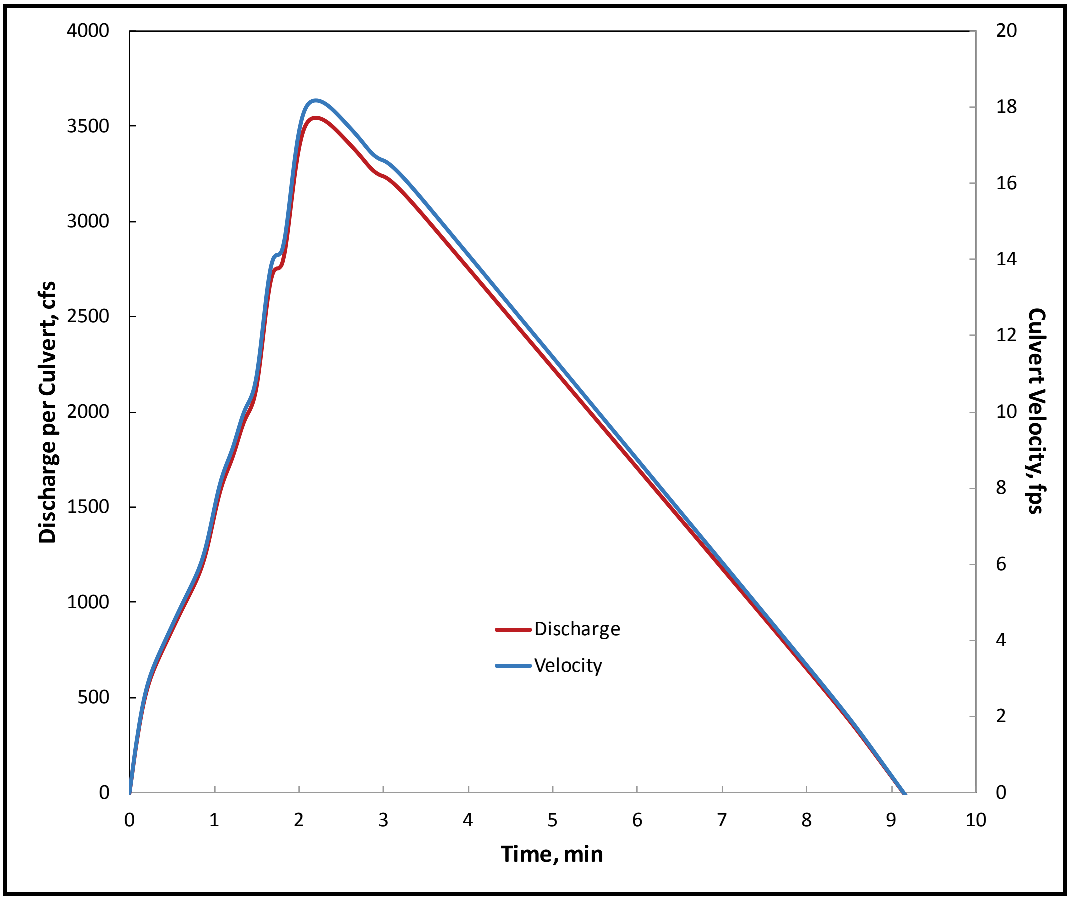


6.3 Lock Performance at Design Conditions

The numerical model results for the design lift of 24 ft, where the river conditions were upper pool el 590 and lower pool el 566, were used to compare the efficiency of the filling system to that of the emptying system, and to evaluate the differences in operating normal- or single-valve schedules. The normal-valve schedules for filling and emptying opened the valves in 3 min, whereas the single-valve schedule for both filling and emptying opened the vertical-lift valve in 4 min.

The lock filled in 8.4 min during a 3 min normal-valve operation and in 16.4 min during a 4 min single-valve operation. The head on the filling valve was greater during single-valve operation compared to a normal-valve operation. The result is seen in the maximum flow rate of 3,600 ft^3/sec compared to 3,430 ft^3/sec per culvert with a normal-valve operation.

Figure 29. Culvert discharge and velocity during normal-valve emptying, 3 min valve time, upper pool el 590, lower pool el 566.



A normal-valve schedule emptied the lock in 8.0 min and a single-valve operation emptied it in 15.7 min, slightly less than twice the normal-valve emptying time. The maximum discharge during normal-valve emptying operations was 3,540 ft^3/sec per culvert, and was 3,720 ft^3/sec during a single-valve operation.

The valves are opened in 3 min during normal-valve operations and the lock filled in 8.4 min. The emptying system was slightly more efficient such that with a normal-valve operation the lock emptied in 8.0 min, 0.4 min less than for normal-valve lock filling.

Single-valve operations determined that the lock filled in 16.4 min and emptied in 15.7 min. This again showed that the emptying system was more efficient than the filling system. The lock emptied about 4 % faster than it filled when single-valve schedules were used to control the filling and emptying flows.

Figure 30. Pressure head in the culverts during single-valve emptying, 4 min valve time, upper pool el 590, lower pool el 566.

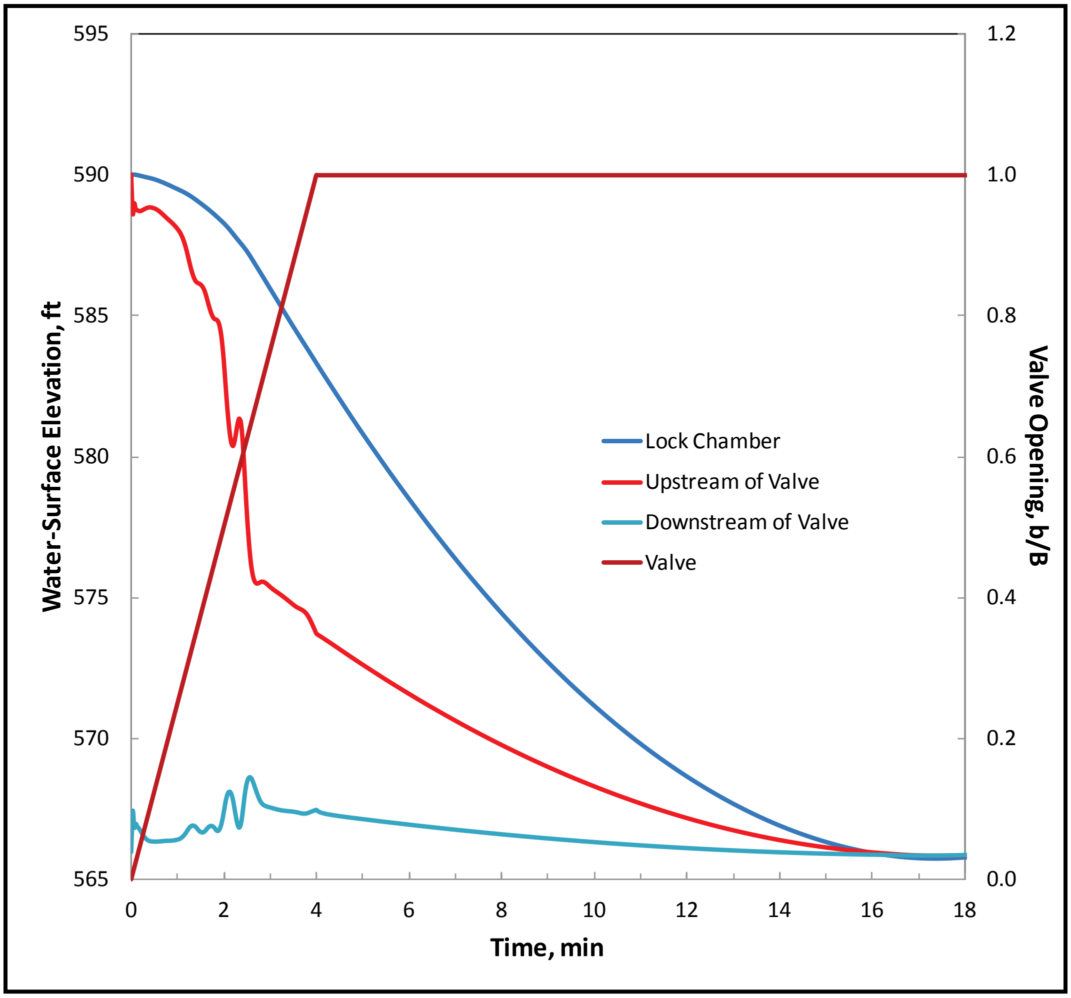
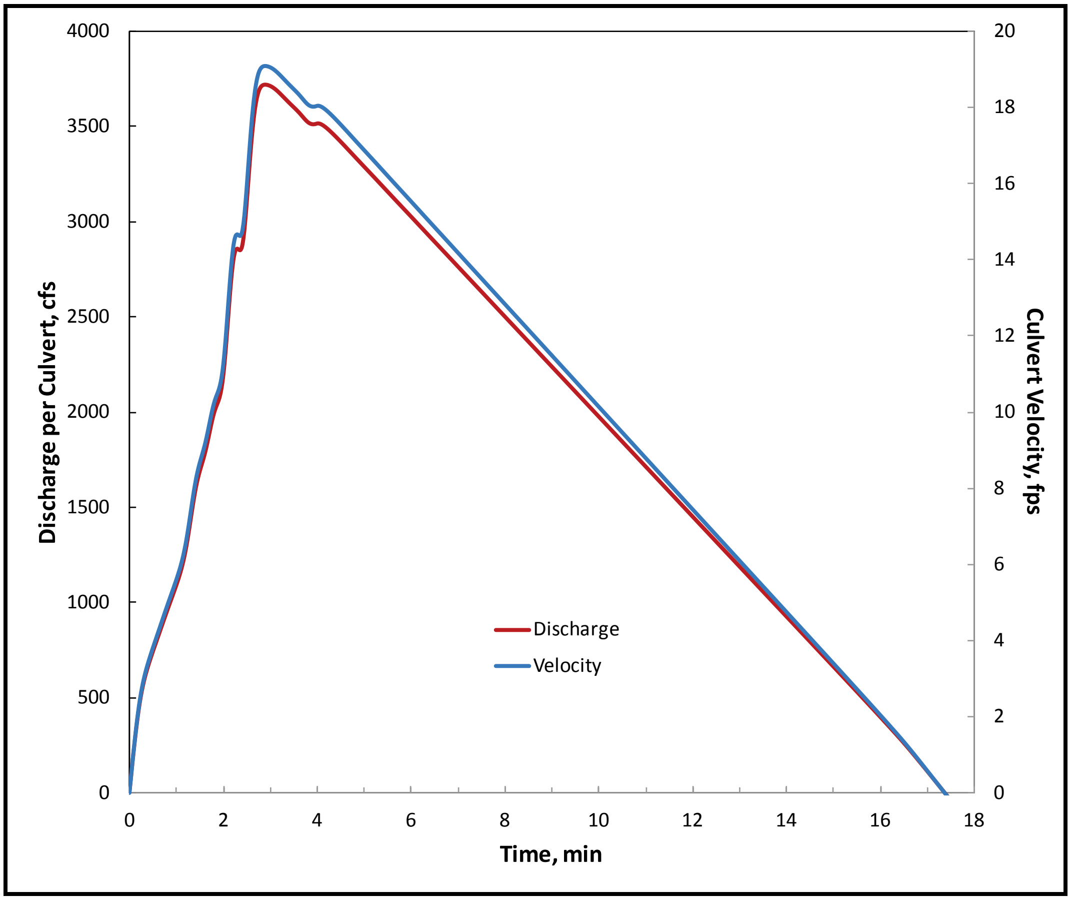


Figure 31. Culvert discharge and velocity during single-valve emptying, 4 min valve time, upper pool el 590, lower pool el 566.



7 Summary and Conclusions

This evaluation of the Marmet Lock has determined that the hydraulic conditions within the filling and emptying system for normal operations are not much different than what was anticipated during design. The numerical model LOCKSIM showed the prototype lock filled in 8.4 min and emptied in 8.0 min with a 24 ft lift. The lock culvert system experienced peak average velocities near 18 ft/sec. Field experiments found that the project valves are operated in a manner that virtually eliminates over-travel of the lock chamber water surface, thus avoiding a reverse head on the lock chamber miter gates.

The design 24 ft lift with river conditions of an upper pool el 590 and a lower pool el 566 found that 3 min normal-valve fill operations reached total discharges near 6,900 ft^3/sec. Normal emptying operations maximum total discharge was near 7,100 ft^3/sec.

1. Field data were combined with fundamental hydraulic engineering to evaluate the Marmet Lock filling and emptying system.
2. Valve operation of opening and then closing, such as the valve schedule for Test F3 for filling (Figure 17) and Test E1 for emptying (Figure 19), virtually eliminated over-travel during filling and emptying.
3. Filling time with the design conditions of a 24 ft lift was 8.4 min and emptying time was 8.0 min. This compared well with the design objective of providing a construction cost-saving innovative lock system that provided the efficiency needed to serve the needs of the USACE and the towing industry.
4. Pressures and discharges were computed throughout the entire filling and emptying system with design lift conditions and normal- and single-valve operations. No adverse pressures were computed during these tests.
5. Although guidance recommends using reverse tainter valves, geometric constraints forced the use of vertical-lift valves at Marmet Lock. The vertical-lift valves should continue to be inspected regularly due to their repetitive use, and because of the USACE limited experience controlling lock culvert flow with valves such as these.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2015	Final report	

4. TITLE AND SUBTITLE
Hydraulic Evaluation of Marmet Lock Filling and Emptying System, Kanawha River, West Virginia

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CHL TR-15-2

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A hydraulic analysis of the Marmet Lock filling and emptying system was performed. Evaluation of the culvert system was considered important because the lock design is a new In-chamber Longitudinal Culvert System (ILCS) that is found only on one other project, the Ohio River's new McAlpine Lock. The purpose of this study was to evaluate the hydraulic conditions within the lock filling and emptying system during locking operations. A numerical model of the lock culvert system was developed to provide velocity and pressure information throughout the system. The model was validated with field data collected earlier in the study. Hydraulic information for both filling and emptying operations with various valve operations was computed. The numerical model results indicate that the hydraulic conditions are not significantly different from those anticipated during the project's design phase.

15. SUBJECT TERMS
Filling and emptying system
Kanawha River
Navigation
Hydraulics
Lock design
Inland waterways
Marmet Lock and Dam

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		56	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18